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Direct-Current Machine Design

Being Instructions for the Design of Motors and Generators

BY

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PART I.

Design of Direct-Current Dynamos and Motors

PREFACE.

This volume is especially prepared for self-instruction in the art of designing direct-current machinery. Care has been taken to remain strictly within the province of design; the reader being assumed to possess knowledge of the principles of electricity and magnetism, and to be familiar with the theory of operation of electrical machines. The designs are carried out according to methods developed in actual practice and are supplemented by data and dimensions of lines of machines actually built by several of the largest American and European companies. The book is divided into two parts; one treating the design of direct-current machines, and the other that of alternating-current machines; each part being followed by a list of questions which clearly bring out the important points to be remembered.

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SYMBOLS

USED IN DYNAMO CALCULATION.

The following is a list of the principal symbols used in connection with dynamo calculations:

AT = Total number of ampere turns.
at_a = Ampere turns required for armature core.
at_g = “ “ “ “ air gaps.
at_m = “ “ “ “ magnet frame.
at_r = “ “ “ “ armature reaction.

B_a = Radial thickness of armature core.
$\mathbf{B}_a$ = Magnetic flux density in armature core.
$\mathbf{B}_g$ = “ “ “ “ air gaps (field density).
$\mathbf{B}_m$ = “ “ “ “ magnet frame.

C = Current.
c = Circumferential current density.
$C.\ M.$ = Circular mils.

D_a = Diameter of armature core.
d_a = “ “ “ conductor.
D_m = “ “ magnet core.
d_m = “ “ “ wire.

E = E. M. F. of armature.
E' = Counter E. M. F. of motor.
Eff = Efficiency.
ε = Factor of eddy current loss in armature.

f = Frequency.
Φ = Flux.

h_a = Height of winding space on armature (depth of slot).
$H.\ P.$ = Horse-power.
η = Factor of hysteresis loss in armature.

$K.W.$ = Capacity of dynamo in kilowatts.
k = Percentage of power loss in armature.

L_a = Length of armature core.
l_a = “ “ active armature conductor.
l_A = Total length of armature conductor.
L_m = Length of magnet core.
l_m = “ “ “ wire.
L_M = “ “ magnetic circuit.
l_t = “ “ mean turn of wire on magnets.
λ = Factor of magnetic leakage.

M = Mass of iron in armature core.
m = Ratio of length to diameter of armature core.
m' = “ “ radial thickness to diameter of armature core.

N = Number of inductors on armature.
n = “ “ revolutions per second.
n_1 = “ “ “ “ minute.
n_P = “ “ pairs of magnet poles.
n_p = “ “ “ “ parallel armature circuits.

R_a = Total resistance of armature wire.
r_a = Resistance of armature winding, cold.
r_a' = “ “ “ “ warm.
ρ = Specific resistance of wire (ohms per foot).

S_a = Cooling surface of armature.
S_m = Cross-section of magnet frame.
S_w = Total area of winding space on armature.
S_w' = Available area of winding space on armature.
s = Specific cooling surface of armature.

v = Peripheral velocity of armature.

W = Capacity of dynamo, in watts.
w_a = Watts consumed in armature winding.
w_e = “ “ by eddy currents.
w_h = “ “ “ hysteresis.
wt = Weight, in pounds.

THE DESIGN OF DIRECT-CURRENT DYNAMOS AND MOTORS

INTRODUCTION.

1. Branches of Science Involved in Dynamo Design.—The following discussion of the design of dynamos and motors will be confined to the consideration of direct-current machines.

The design of a dynamo and motor relates to three essential parts: first, the *armature* carrying the conductors in which the electric energy is generated or absorbed; second, the *field magnet* that produces the magnetic field or flux in which the armature revolves; and third, the various *mechanical parts* and arrangements necessary to carry out the electrical and magnetic actions. Thus, three great branches of science—*electricity*, *magnetism*, and *mechanics*—are involved.

2. General Method to be Followed.—In taking up the design of a dynamo or motor, the mind should not be allowed to jump at conclusions or immediately settle upon some particular solution of the problem. The question should be considered from all points of view before any one point is decided. One should also endeavor to be free from prejudices and not blindly follow custom. On the other hand, it is a mistake to attempt radical or sensational departures from well-established practice. By always striving for simplicity and directness, the latter danger is generally avoided.

Certain quantities entering the calculations are not prescribed and must be *assumed* by the designer. If he is experienced, usually the first or second assumption of the variable quantities will lead to a satisfactory result.

The beginner, however, will generally be so wide of the mark that numerous recalculations are necessary to learn the effect of the different variable quantities upon the result, and to arrive at a successful solution. The more trials that are made intelligently in this way, the more information is gained by the student. It is not wise, however, to carry out preliminary calculations elaborately, because it wastes time and is discouraging if they are found to be incorrect. One should have the moral courage to change or discard drawings and results when they are not right.

It is a common mistake to trust blindly to formulas which are merely shorthand, and, unless they are thoroughly understood, are very likely to give wrong results. Each quantity should be carefully scrutinized to make sure of its significance and relation to the other factors involved.

3. Parts of a Dynamo or Motor.—The chief parts of these machines are the *armature* and the *field magnet.* The latter is usually stationary, and is combined with the base and bearings to form what is called the *frame* of the machine. In alternating current machines it is quite common to have the field magnet revolve and the armature stationary. This arrangement is very rarely attempted in direct-current dynamos or motors, because it necessitates the rotation of the brushes and renders their adjustment extremely difficult.

It is better to consider the armature first, because it is the most important element of the machine, and the other parts should be made to conform to it. As a matter of fact, any part will have to be considered with reference to the others, but it is necessary to take up one at a time, and usually to go back and modify the first ones after the others have been evolved.

4. Forms in which the Problem presents Itself.—In most cases the object of designing a dynamo or motor is to produce a machine which will fulfill certain specified conditions.

A *generator* is usually required to develop either a given current, C amperes, or a certain electrical power, $K. W.$ kilowatts, at a given voltage, E, and at a prescribed speed, n, revolutions per minute. The value of the current, if the problem is given in the latter form, may be found by dividing the output, in watts, by the $E. M. F.$, in volts; or in symbols:

$$C = \frac{1{,}000\, K.\ W.}{E} \quad \text{(1)}$$

where C = current, in amperes;
$K.\ W.$ = electrical power, in kilowatts;
E = E. M. F., in volts.

A *motor* is ordinarily designed to develop a given number of mechanical horse powers, $H.\ P.$, at a certain speed, n, revolutions per minute, when supplied by a given voltage, E.

5. Method of Motor Calculation.—In order to enable a motor problem to be treated in the same manner as the design of a generator, the H. P. may be converted into K. W. by multiplying the former by .746; and the counter E. M. F., E', of the motor may be assumed to be from *1* to *5* per cent. less than the supply voltage, E, depending upon the size and type of the motor. The difference between E and E' is usually between *1* and *2* per cent. for large machines of *100 H. P.* and more, and about *4* or *5* per cent. for small machines of *1* and *2 H. P.* If the speed of the motor is abnormally low, to enable it to be directly connected to printing presses, blowers, etc., the difference between the direct and counter E. M. F. is correspondingly greater. The following values, therefore, enable a motor to be treated the same as if it were a problem in dynamo design:

Output: $K.\ W. = .746\ H.\ P.$ ....(2)
Counter E. M. F.: $E' = .95\ E$ to $.99\ E$ ....(3)
Current: $C = \frac{746 \times H.\ P.}{E \times Eff.}$ ....(4)

In (4) the average values of the *electrical* efficiency of motors given in Table **1** may be used:

TABLE 1.

EFFICIENCIES OF MOTORS.

Size of Motor.	Average Electrical Efficiency.	Average Commercial or Total Efficiency.
½ H. P.	.90	.75
1 "	.92	.80
5 "	.94	.85
10 "	.95	.87
20 "	.96	.88
50 "	.97	.91
100 "	.98	.92
200 "	.98	.93
500 "	.985	.94
1000 "	.985	.95

In Table **1** the average values of the *commercial* or *total* efficiencies of motors of various sizes are added for comparison and reference.

It is possible to design a motor in terms of H. P., torque, etc., instead of K. W., current, etc., but the advantage of using the same formulas for both kinds of machines warrants the adoption of the above method. Any errors in assuming E' or the efficiency are not likely to be more than a few per cent., and can be subsequently corrected.

6. Forms of Armature.—The four principal types of armature—*ring, drum, pole,* and *disc*—have already been described in previous lessons. At the present time, only the first two forms are important, the pole armature not being used except in small toy motors or dynamos, and the disc armature being adopted in but a single type of direct-current machine—the *Desroziers* dynamo made in France.

The chief advantage of the ring armature lies in the fact that the coils which differ considerably in potential are widely separated from one another. For this reason the ring armature is preferable for very high voltage machines, such, for example, as series arc lighting generators. Formerly the ring armature had the advantage over the drum that single coils could be taken off and replaced without disturbing the rest of the winding; but the general use of *formed* coils for drum armatures, which is now the common practice, enables the same thing to be done in their case with almost equal convenience.

The great advantage of the drum form is due to the fact that it can be directly and securely mounted upon the shaft. In some cases armature cores are carried upon spiders, so that they may be wound in either the ring or drum fashion as desired. The latest practice seems to tend toward the adoption of the drum in preference to the ring type for small and medium size machines. This matter will be understood more clearly when the details of form and construction have been more fully considered.

7. **Armature Cores.**—If the core of the armature were made of one solid piece of iron, currents would be set up in it, since the outer portions of the core cut magnetic lines, exactly as the armature conductors themselves. The useless currents thus generated, called *Foucault* or *eddy* currents, consequently flow in the same direction as the armature currents, that is to say, ordinarily in a direction parallel to the shaft of the armature. In order to prevent these eddy currents, which consume power and also cause heat, from flowing, it is, therefore, necessary to intercept their path by subdividing, or **laminating,** the core perpendicularly to the shaft.

The usual plan is to build up the core of discs or rings of sheet iron, lightly insulated from one another, so that the magnetic lines can pass freely through each disc, but the eddy currents which tend to flow perpendicularly across the discs are stopped by the insulation between the latter. Since the eddy currents tend to flow in the same direction as the useful currents in the conductors, the core should always be laminated parallel to the lines of force and to the direction of the motion.

8. Wire Cores.—Iron *wire* has been employed for armature cores, and possesses the advantage of very complete subdivision and of being easily wound in a ring or drum of any desired size or form. A wire core has, however, the disadvantages of promoting magnetic discontinuity, of constituting a poor mechanical construction, and of entailing loss of space between the wires, especially if they are of circular cross-section.

9. Core Discs.—Discs or rings are almost always used for armature cores, and are punched or cut out of the softest sheet iron or mild steel, a special quality being manufactured for this purpose. The thickness is usually from .01 to .03 inch, a standard size being .022 inch. The same thickness is often employed for all sizes of machines, including the largest as well as the smallest, being adopted because it is convenient to handle and to punch, and is sufficiently thin to reduce the eddy currents to a small value.

For armatures less than about 2 feet in diameter, each core disc is a complete ring in one piece, but armatures of larger diameter are built up of a number of sectors in order to facilitate their punching and handling.

10. Effective Cross-Section of Armature Core.—The laminæ were formerly insulated from each other by *tissue paper*, *paint*, *varnish*, or *rust*, but the usual practice at present is to simply rely upon the *oxide coating* on the surface of the discs.

An armature core composed of such sheets, and forced together by heavy hydraulic or screw pressure, is found to contain from 85 to 95 per cent. of its volume of iron, the rest being made up of insulation, scale, and small air spaces due to slight inequalities in the sheets; hence the effective cross-section or magnetic carrying capacity of such a core is from 15 to 5 per cent. less than that of an equal volume of solid iron of the same permeability.

The effective cross-section of the armature core is further reduced by the presence of ventilating spaces, or holes, which are often left in the armature core.

11. Advantages of Toothed Armatures.—In the **toothed** or **slotted** armature (Fig. 1), which is now largely superseding the **smooth** form, the conductors are wound in the slots between teeth or projections formed upon the main body of the core. This type, also called the *Pacinotti armature,* after its inventor, has the following advantages over the smooth core:

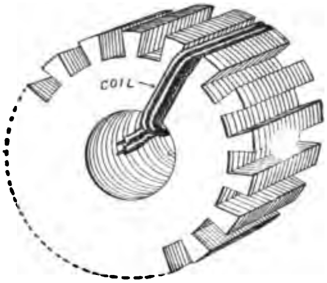


FIG. 1.—TOOTHED ARMATURE.

1. The reluctance of the air-gap is reduced to a minimum.
2. The armature conductors are protected from injury.
3. The conductors are firmly held in place and cannot slip on the core by the action of the electro-dynamic force exerted upon them.
4. Eddy currents in the armature inductors are avoided, since the magnetic lines snap across the latter instantly.*
5. If the teeth are practically saturated by the field magnetism, they oppose the shifting of the lines by *armature reaction.*

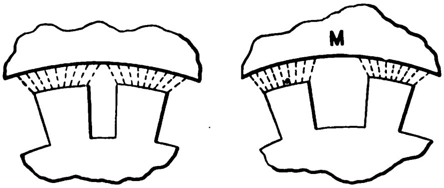
---

* This point will be considered further under the head of *Eddy currents in armature inductors.*

12. Disadvantages of Toothed Armatures.—The disadvantages of the toothed armature core are:—

1. It is somewhat more expensive to make.
2. The teeth tend to generate eddy currents in the pole-pieces.
3. The self-induction of the armature coils is increased.

The second difficulty can be practically overcome by making the distance between the teeth at their ends not more than 2 to 3 times the air-gap, so that the lines can spread from the corners of the teeth, and become nearly uniform on the pole-faces, as represented in Fig. 2. If the slots near the periphery are wider than three times the length of the air-gap, as shown in Fig. 3, there will be spaces, *M*, on the pole-pieces, where there are practically no lines.



FIGS. 2 AND 3.—DISTRIBUTION OF MAGNETIC LINES ON POLE-FACE WITH TOOTHED ARMATURE, UNDER VARYING CONDITIONS.

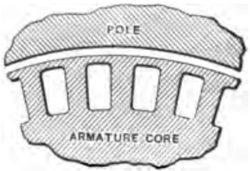


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FIG. 4.—PERFORATED ARMATURE.

These spaces will move across the pole-faces, and the shifting field thus produced tends to induce eddy currents in the pole-pieces, which should in such cases be laminated or grooved in the direction of motion of the armature, in order to reduce the flow of these wasteful currents. In some cases the entire armature has been covered with a thin layer of iron wire, producing a continuous magnetic surface. The same effect is obtained by perforating the edge of the armature core, as shown in Fig. 4, instead of having open slots. The objections to both of these latter forms are their increased self-induction and the fact that a certain magnetic leakage occurs through the iron outside of the inductors.

PRELIMINARY CALCULATION OF ARMATURE.

13. Preliminary Determination of Dimensions of the Armature.—There is no absolute rule for determining the size of an armature, since it depends upon many conditions which cannot be included in a formula or covered in any general way; nevertheless there are several facts that will aid us in assuming an approximate size, which can be modified later if found incorrect. In point of fact, as already stated in the introduction, it is almost an advantage if several different sizes are tried before arriving at the right one, since it gives a broader view of the question and enables one to choose finally the best size, all things considered.

The chief points to consider in arriving at the size of an armature are: 1. *Peripheral speed.* 2. *Cooling surface.* 3. *Space for inductors.* 4. *Surface covered by pole-pieces.*

14. Peripheral Speed of Armature.—One guide in obtaining the diameter of an armature is the fact that the peripheral velocity, v, must be kept within the limits established by practice, that is, between *1,500* and *6,000* feet per minute, *3,000* being a common value. Since the peripheral velocity of an armature may be expressed as the product of the armature circumference, in feet, by the number of revolutions per minute, or

$$v = \frac{D_a \pi}{12} \times n_1, \qquad (5)$$

the approximate diameter, D_a, of the armature, in inches, can be found by the following equation, when n_1, the number of revolutions per minute, is known:

$$D_a = \frac{12v}{\pi n_1} = 3.8 \times \frac{v}{n_1} \qquad (6)$$

The value of v in (6) should be taken within the limits given in Table 2, according to the kind of machine.

TABLE 2.

ARMATURE SPEEDS FOR VARIOUS KINDS OF DYNAMOS.

Kind of Machine.	Peripheral Velocity, in feet per minute.	
	Usual Limits.	Average.
High-Speed Ring Machine	3,000 to 6,000	4,500
Medium-Speed Ring Machine	2,000 " 4,000	3 000
Drum-Armature Machine	2,000 " 4,000	3,000
Low-Speed Direct-Driven Machine	1,500 " 3,000	2,250

The lower limit in all cases refers to small dynamos, while the upper limit refers to large machines, the average in each instance corresponding to a size of about *100 K. W.* For machines below that size, therefore, use a value smaller than the average, and for machines above *100 K. W.* take a value between the average and the upper limit. The general average of *3,000* feet per minute is a good practical value for *belt-driven drum armatures* of from *10* to *300 K. W.* capacity, and for *direct-driven machines* of from *500 K. W.* output up; while for *high-speed ring armatures* it applies only to sizes smaller than ½ *K. W.*

15. Approximate Cooling Surface of Armature.— Another method of predetermining the size of an armature is based upon the surface required to dissipate the heat generated within the armature. There is some uncertainty as to what surface we are to consider the cooling surface of an armature.

For a *drum armature* we will here take it to be the sum of the cylindrical surface of the armature core and of the area of a circle the diameter of which is the external diameter of the core, or

$$S_a = D_a \pi L_a + D_a^2 \frac{\pi}{4}, \quad \ldots\ldots\ldots\ldots\ldots (7)$$

where D_a is the diameter, and L_a the length of the armature core. In a drum armature, then, only one of the two end surfaces *A*, *B*, Fig. 5, is taken into account, which is done for the reason that the surface *B*, which is near the commutator *C*, receives heat from the latter by radiation and convection as well as by conduction through the armature conductors. It is, therefore, wise to consider this surface, *B*, as part of the cooling surface of the commutator, which is usually the hottest part of the machine.

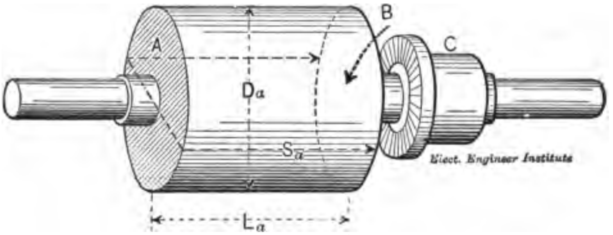

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FIG. 5.—COOLING SURFACE OF DRUM ARMATURE.

Expressing in the above formula (7) the length L_a as a multiple, or ratio, of the diameter, or $L_a = mD_a$, where m is this shape-ratio of the armature, the approximate cooling surface of a drum armature can be expressed as:

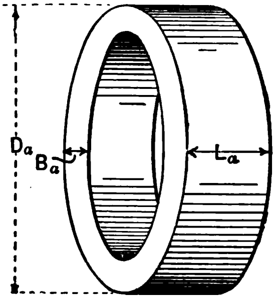

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FIG. 6.—COOLING SURFACE OF RING ARMATURE.

$$S_a = D_a \pi m D_a + D_a^2 \frac{\pi}{4} = D_a^2 \pi (m + \tfrac{1}{4}), \ldots\ldots\ldots\ldots (8)$$

which contains only the diameter and the shape-ratio.

In the case of a modern *ring armature*, usually the total core surface is open to the access of air; hence, the entire core surface can in most cases be considered as cooling surface. If, however, the construction of the armature is such that the inner surface or one of the end surfaces is covered up, the area so covered must be excluded from the calculation of the cooling surface. The total surface of a ring having a diameter D_a, a length L_a, and a radial depth B_a, Fig. 6, is given by the formula:

$$S_a = (D_a - B_a)\pi \times 2(L_a + B_a) \qquad (9)$$

Expressing both the length and the radial thickness of the ring as multiples of its diameter, $L_a = mD_a$ and $B_a = m'D_a$, we obtain:

$$\begin{aligned} S_a &= 2\pi \times (D_a - m'D_a) \times (mD_a + m'D_a) \\ &= 2\pi \times D_a^2 \times (1 - m') \times (m + m') \qquad (10) \end{aligned}$$

16. Determination of Armature Diameter by Cooling Surface.—It is found that from ½ to 1 square inch of cooling surface is needed to liberate the heat resulting from each watt of power lost in the armature. This includes not only the copper, or C^2R, loss due to the resistance of the armature winding, but also the iron loss, or core loss, due to hysteresis and eddy currents. These losses are not definitely known in the beginning, but it is reasonable to assume that they will be from *1* to *3* per cent. of the total power in large machines of *500 K. W.* and over; *3* to *5* per cent. for machines of about *100 K. W.*; *4* to *6* per cent. for sizes of about *50 K. W.*; *5* to *8* per cent. for *10 K. W.*; *6* to *10* per cent. for *5 K. W.*; *8* to *12* per cent. for *1 K. W.*; and up to *20* and even *25* per cent. for *very small* machines, such as battery motors, etc.

The cooling surface, in square inches, required in any case is, therefore:

$$S_a = s \times k \times W, \qquad (11)$$

in which W = capacity of dynamo, in watts;
s = specific cooling surface,
= *.5* to *1* square inch per watt of power loss;
and k = percentage of power loss in armature (see Table 3 for average values).

TABLE 3.

POWER LOSS IN ARMATURES OF VARIOUS SIZES.

Size of Machine.	Percentage of Power Loss, *k*.	
	Usual Limits.	Average.
Above 500 K. W	.01 to .03	.02
Between 500 and 100 " "	.02 " .05	.035
" 100 " 50 " "	.03 " .06	.045
" 50 " 10 " "	.04 " .08	.06
" 10 " 5 " "	.05 " .10	.075
" 5 " 1 " "	.06 " .12	.09
Below 1 " "	.10 " .20	.15

Substituting in formulas (**8**) and (**10**) the value of S_a given in formula (**11**), we obtain:

for drum armatures: $D_a^2\pi(m+\frac{1}{4})=s\times k\times W$, or

$$D_a=\sqrt{\frac{s\times k\times W}{\pi(m+\frac{1}{4})}};\ldots\ldots\ldots\ldots(\mathbf{12})$$

for ring armatures: $2\pi D_a^2(1-m')\,(m+m')=s\times k\times W$, or

$$D_a=\sqrt{\frac{s\times k\times W}{2\pi(1-m')\,(m+m')}}\ldots\ldots(\mathbf{13})$$

Since in formula (**12**) one of the end surfaces is neglected, whereas in (**13**) the entire core surface is considered as cooling surface, the actual cooling surface of a drum armature is larger than that given by (**8**), while the effective cooling surface of the ring armature is smaller than the value found by (**10**). Consequently, in order to reduce both formulas to the respective actual cooling surface, it is necessary to take a somewhat larger value of *s* for a ring armature than for a drum, in spite of the fact that the former, owing to its better ventilation, will require less cooling surface than the latter in order to dissipate equal amounts of heat. The student should use $s = .5$ to $.75$ in (**12**) for *drum* armatures, and $s = .75$ to *1* in (**13**) for *ring* armatures.

In practice the shape-ratios *m* or *m'* in the above formulas are usually known from previous designs of the same type; but if their approximate values are not given in this manner, a number of assumptions of *m* and *m'* may be made within the limits compiled in the following Table **4**:

TABLE 4.

SHAPE-RATIOS FOR DIFFERENT ARMATURES.

Kind and Size of Armature.	Ratio *m* of Length to Diameter.	Ratio *m'* of Radial Thickness to Diameter.
Ring, above 100″ Diameter....	.15 to .25	.05 to .10
Ring, from 100″ to 20″ Diameter....................	.25 " .5	.08 " .25
Ring, below 40″ Diameter ..	.25 " 1.	.10 " .30
Drum, above 30″ "	.75 " 1.5	—
Drum, from 10″ to 30″ Diameter....................	.75 " 1.75	—
Drum, below 10″ Diameter....	1. " 2.	—

A comparison of the value calculated from (**12**), or (**13**), respectively, with that previously obtained from (**6**), will assist the designer in deciding upon the final diameter of the armature. The student, who naturally lacks the experience of a professional designer, should also consult the dimensions of existing machines of similar output and speed, tables of which are given in Par. **19**.

17. Example of Drum Armature.—*Find the approximate diameter of a drum armature for a* **50 K. W.** *belt-driven generator to run at* **500** *revolutions per minute.*

Solution.—Taking the value of *3,000* for the peripheral velocity. in accordance with Par. **14,** we have from formula (**6**) :

$$D_a = 3\ 8 \times \frac{3000}{500} = \mathbf{22.8} \text{ inches.}$$

According to Table **3,** the percentage of power loss in the armature of a 50 K. W. dynamo ranges between .04 and .08; a good value for a high-class machine therefore, is $k = .06$. The specific cooling surface, according to formula (**11**), can be taken between .5 and 1 square inch per watt; using the average value, we have $s = .75$. For a drum armature of the above found diameter, a good shape-ratio is $m = 1.2$ (see Table **4,** page 14); hence, the approximate diameter of the armature, from formula (**12**):

$$D_a = \sqrt{\frac{.75 \times .06 \times 50.000}{3.1416 \times (1.2 + \frac{1}{4})}} = \sqrt{\frac{2250}{4.5553}} = \mathbf{22.2} \text{ ins.}$$

This being practically the same as the value obtained above from formula (**6**), the nearest even value between the two results, or $D_a = \mathbf{22\frac{1}{2}''}$, may be decided upon.

18. Example of Ring Armature.—*Compute the diameter of a ring armature for a* **200 K. W.** *direct-driven generator which is to run at* **175** *revolutions per minute.*

Solution.—The peripheral velocity should in this case be taken $v = 2.250$ feet per minute (see Table **2,** page 10); hence, we have by (**6**) :

$$D_a = 3.8 \times \frac{2250}{175} = \mathbf{48.8} \text{ inches.}$$

For the case in hand, the specific cooling surface should be taken between .75 and 1; let us assume $s = .8$. The percentage of power loss in the armature of a direct-driven 200 K. W. dynamo is about 4 per cent.; hence, $k = .04$. From Table **4,** the average ratio of length to diameter in this case is $m = .375$, and the average ratio of radial breadth to diameter is about $m' = .15$. Inserting these values into (**13**), we have:

$$D_a = \sqrt{\frac{.8 \times .04 \times 200,000}{6.2832 \times (1 - .15) \times (.375 + .15)}} = \sqrt{\frac{6400}{2.8}} = \mathbf{47.8} \text{ ins.}$$

The diameter required to give an adequate cooling surface being somewhat smaller than that for which the peripheral velocity is just right, a value between the two results obtained may be taken. Their average is about

$$D_a = 48\tfrac{1}{2} \text{ inches.}$$

19. Tables of Dimensions of Modern Dynamos.—In order to guide the student in the selection of values for the various variable quantities which he has to assume in the course of a dynamo calculation, tables of dimensions of modern machines are here given, covering all the usual cases of dynamo design. The tables include drum as well as ring armature machines, and give the principal dimensions for high, medium, and low speeds, for all ordinary sizes. In Tables **5** to **10** the dimensions of some of the machines of the *Crocker-Wheeler*, *General Electric*, and *Westinghouse Companies* are compiled, and in Tables **11** and **12** the armature dimensions of all the machines contained in Tables **5** to **10** are tabulated according to size and speed, so as to be readily employed for reference.

In the case of an example calling for the design of a machine which is to run at a speed not sufficiently near any of the speeds given for that output in Tables **11** or **12**, a standard of comparison may be obtained by interpolating between the next higher and lower speeds found for the same output and type of armature. For instance, if a 200 K. W. ring-type dynamo is to be calculated for a speed of 300 revs. per min., the result of equations (**5**) and (**9**), or (**10**), respectively, should be compared with the diameter obtained by interpolating between the dimensions given in Table **11** for the 200 K. W. high-speed ring armature and the 200 K. W. medium-speed ring armature, thus:

Diameter, 200 K. W. ring armature, 450 revs per min. .... 32½ ins.
" 200 " " " 175 " " " .... 50 "
" 200 " " " 300 " " " by interpolation:

$$32\tfrac{1}{2} + \left[\frac{450 - 300}{450 - 175} \times \left(50 - 32\tfrac{1}{2}\right)\right] = 32\tfrac{1}{2} + 9\tfrac{1}{2} = \mathbf{42} \text{ inches.}$$

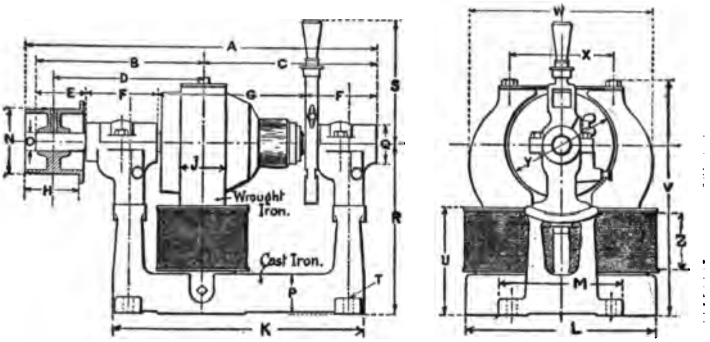

FIG. 7.—CROCKER-WHEELER BIPOLAR MOTOR.

TABLE 5.

DIMENSIONS OF CROCKER-WHEELER BIPOLAR MEDIUM-SPEED RING-ARMATURE MOTORS. (See Fig. 7.)

H. P.	K.W.	R. p. m.	Weight.	A	B	C	D	E	F	G	H	J	K	L
1/12	.1	1800	19	7 11/16	3 13/16	3 11/16	3	1 5/8	1 1/8	3 5/8	1	2	5 3/4	5 1/8
1/8	.15	1600	27	9 7/8	4 11/16	4 27/32	4 1/8	1 1/4	1 7/8	4 1/8	1	1 5/8	7 1/4	6 1/2
1/4	.25	1400	70	14 15/16	6 5/8	7 11/16	6 1/8	1 1/2	3 1/8	6 5/8	2 1/4	1 7/8	11 5/8	8 5/8
1/2	.5	1200	100	17 3/4	8 3/4	9 1/16	7 3/16	2 5/8	3 3/4	7 11/16	3	2 1/8	13 1/16	10
1	1.	1000	205	19 1/4	9 1/4	9 3/4	7 3/4	2 11/16	3 7/8	8 9/16	3 1/4	2 3/16	14 7/16	13 1/4
2	1.5	975	288	22 1/2	10 5/16	11 3/4	8 3/4	2 3/4	4 7/16	10 7/16	4	3 5/16	17 1/4	14 1/4
3	2.25	950	410	26 13/16	11 13/16	14 5/8	10 5/8	3 1/8	5	13 1/16	4 1/4	3 9/16	21 7/16	16 1/4
5	4.	925	510	28 3/16	12 31/32	14 13/16	10 7/8	3 25/32	5	14	5	4 13/16	22 5/8	19 1/4
7 1/2	6.5	875	760	33	15 1/16	16 15/16	13 1/16	4	5 3/4	16 1/8	6	5 5/8	26 1/4	21 1/4
10	8.5	850	920	36 1/2	17	18 1/2	14 1/2	5	6 1/4	17 1/2	7	6 1/4	28 1/2	23 3/16

H. P.	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z
1/12	3 1/8	1 1/2	5/8	1	9/16	5 11/16	..	1/4	3 15/16	7 7/8	5 1/8	3	3	2 3/4
1/8	4 1/2	1 1/2	5/8	1 7/16	1 3/16	6 1/8	..	5/16	4 1/16	8 1/2	5 7/16	3 3/8	3 13/32	2 1/2
1/4	4 9/16	3	9/16	1 7/8	1 1/2	7 3/4	..	3/8	4 15/16	10 11/16	8 1/4	4 5/8	4 3/4	2 7/8
1/2	6 5/8	3	11/16	2 1/8	2	9	7 13/32	1/2	5 3/4	12 9/16	9 1/2	5 1/2	5 5/8	3 1/2
1	8 3/4	4	7/8	2 13/16	2 1/4	10 5/8	7 13/32	1/2	6 3/4	15	12 7/16	7 1/4	7	3 5/8
2	9	5	1	3 3/16	2 5/8	11 1/16	7 3/4	1/2	6 7/8	15 3/4	13 3/4	8	7 3/4	3 1/2
3	11 1/2	6	1	2 9/16	2 5/8	11 13/16	9 5/8	5/8	7 3/8	18 3/4	13 1/2	7 1/2	8 1/4	4 5/8
5	12	7	1 1/8	3 5/8	2 5/8	13 5/8	9 5/8	5/8	8 1/2	21 5/8	15 1/4	7 1/2	9 3/16	4 7/8
7 1/2	14 1/4	8	1 1/4	4	3 1/8	14 5/8	10 5/8	5/8	9 1/4	23 1/2	17 7/8	7 1/2	10 1/8	4 3/4
10	15 3/4	9	1 1/2	4 1/4	3 1/2	16 1/4	11 1/2	5/8	10 3/16	25 3/4	19 3/16	8 3/4	11	5 1/2

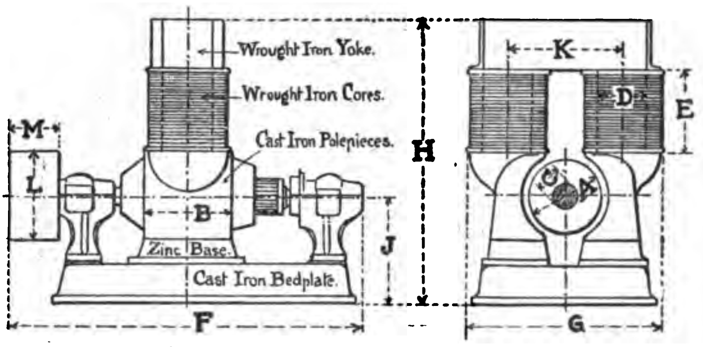

FIG. 8.—EDISON BIPOLAR DYNAMO.

TABLE 6.

DIMENSIONS OF EDISON BIPOLAR HIGH-SPEED DRUM-ARMATURE DYNAMOS AND MOTORS. (See Fig. 8.)

Generator.		Motor.		Weight.	Armature.			Magnets.		Frame.					Pulley.	
K. W.	R. p m.	H. P.	R. p. m.		A	B	C	D	E	F	G	H	J	K	L	M
.5	2400	.5	2100	90	2 5/16	4	11/16	2 5/8	4 1/2	16 5/8	9 1/2	12 1/2	4 5/16	4 7/8	3 1/2	2
.75	2400	.75	2100	120	2 5/8	5	7/8	2 3/4	5 1/2	21 1/4	9 3/4	13 3/4	4 5/16	5 1/2	3 1/2	2 1/2
1.5	2100	1.5	1600	270	3 23/32	6 1/2	15/16	3 3/4	6 3/4	24 1/4	13 1/2	19	7	7 7/16	4	3
3	1900	3	1450	550	4 1/2	8	1 1/8	5	7 5/8	33	17	23	8 1/2	9 1/4	7 1/2	3
6	1800	6	1350	830	5 11/16	9 1/4	1 3/8	5 3/4	8 3/4	38 3/4	20	26 7/8	10 1/16	11	8	4
8.5	1700	9	1325	1090	5 7/8	10	1 5/8	6 5/16	10 5/8	44 1/8	22	30 1/2	11 1/8	12	8 1/2	5
12	1600	14	1275	1470	6 1/4	12	1 7/8	7 3/8	12 1/4	48 5/8	23 1/2	34	12 1/8	12 1/2	9	6
15	1500	17.5	1150	2130	6 3/4	13 1/2	2 1/4	8 1/4	13 5/8	57	25 3/4	38	13 5/8	13 7/8	11 1/4	8
20	1400	24	1100	2880	7 3/4	15	2 1/2	9 1/4	15 1/8	65 3/4	28 5/8	41 3/4	14 5/8	15 1/8	12	9
25	1300	30	950	3570	8 3/4	16 1/2	3	10 1/8	16 1/4	68 1/4	30 1/4	45 1/8	15 5/8	16 1/4	13	10
30	1200	36	880	4340	9 3/16	18	3 1/4	11 1/8	16 7/8	73 1/4	31 5/8	47 5/8	16 1/2	16 3/8	14	11
45	1000	60	750	6800	11 1/16	20 1/2	3 3/4	12 3/4	20 1/8	83 1/2	36	57 1/2	19 1/2	19 3/4	17	12
60	700	70	525	9790	12 7/8	24 1/2	4	15 1/8	23 7/8	92 1/2	40 3/4	65 7/8	21 3/4	22 1/2	24	13
100	650	120	550	16200	16 3/8	25	4 3/4	17 1/4	24	105	47 1/2	73 1/2	24 3/4	26 1/2	26	16
150	450	180	450	31790	23 3/4	26 1/2	5	21 1/2	31	119 1/8	59 1/4	92 1/2	31 3/4	33	44	21
200	450	240	450	39000	23 3/4	31 1/4	7 3/4	23	31	135 1/2	67 3/4	94	31 3/4	37 3/4	44	24

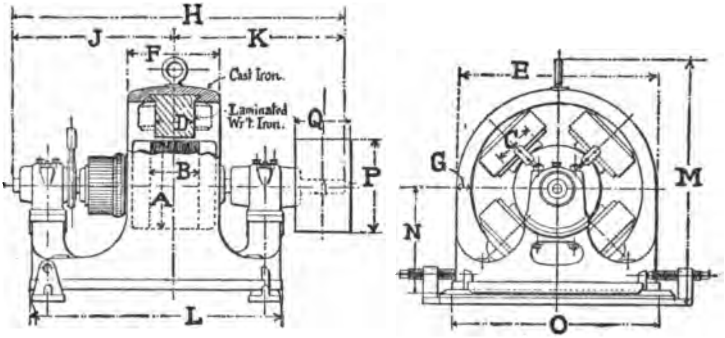

FIG. 9.—WESTINGHOUSE FOUR-POLE DYNAMO.

TABLE 7.

DIMENSIONS OF WESTINGHOUSE FOUR-POLE MEDIUM AND HIGH SPEED DRUM-ARMATURE DYNAMOS AND MOTORS. (See Fig. 9.)

Machine No.	Medium Speed.			High Speed.			Weight.	Armature.			Magnets.	
	K. W.	H. P.	R. p. m.	K. W.	H. P.	R. p. m.		A	B	Nbr. of Slots.	C	D
1	.56	¾	1300	.75	1	1900	190	5¾	2⅝	31	2⅛	2⅛
2	1.5	2	1200	1.875	2½	1700	290	6⅛	3¼	31	3⅜	2¼
3	2.62	3½	1050	3.75	5	1600	550	7¾	4⅝	47	4⅛	3½
4	3.75	5	950	5.62	7½	1350	740	8⅛	5¼	41	5	3⅞
5	5.62	7½	850	7.5	10	1250	940	9⅛	5⅜	47	5¼	4⅛
6	7.5	10	750	11.25	15	1150	1190	10⅛	6	47	5¾	5
7	11.25	15	650	15	20	1050	1550	11⅝	6¼	47	6⅜	7⅛
8	15	20	600	22.5	30	975	2460	13	8	47 & 71	7½	6½
9	.....	...	....	30	40	930	2950	13⅞	8⅛	61	8½	6⅞
10	22.5	30	575	37.5	50	900	3410	15	8⅛	41 & 61	8	7½
11	30	40	550	45	60	850	3900	15¾	8½	47 & 59	8	8
12	37.5	50	550	56.25	75	800	4300	16⅛	9	71 & 55	8½	8⅛

Machine No.	Yoke.			General Dimensions.							Pulley.	
	E	F	G	H	J	K	L	M	N	O	P	Q
1	13¾	5⅛	¾	23	11	11	16½	17⅜	7½	14⅜	3½	2½
2	14¾	6⅛	1	26¼	12⅛	13¾	19⅜	18¾	7⅝	15⅛	5	3
3	18	8⅛	1⅜	32	15¾	16¼	24⅛	22⅞	9⅜	19	6	4
4	19⅛	9⅛	1¾	36	16¾	19¼	26⅝	24⅜	10⅛	20½	8	5
5	21⅛	10	1¾	38	18⅝	19⅝	28½	26⅝	11⅛	22⅜	8	5
6	24	10⅛	2	40¾	19⅜	21⅝	30⅛	30	12⅛	25¼	9	6
7	26⅜	12	2¼	44⅜	20⅞	23⅝	32⅞	32⅛	13¾	27⅞	14	7
8	30¾	13⅛	2⅞	50⅛	25⅛	25⅝	33⅝	36⅜	15⅝	31¾	14	8
9	33	14	3¼	54⅜	25⅞	28⅝	39⅞	40	17	34½	15	11
10	34⅛	14⅛	3⅜	56⅛	26⅝	29⅞	42	41⅛	17⅜	36½	15	11
11	35⅞	14⅝	3 7/16	65½	34⅞	30⅞	47½	43⅜	18⅛	37⅛	20	11
12	37	15¼	3½	66	33¾	32½	47⅞	44	19	38¾	20	11

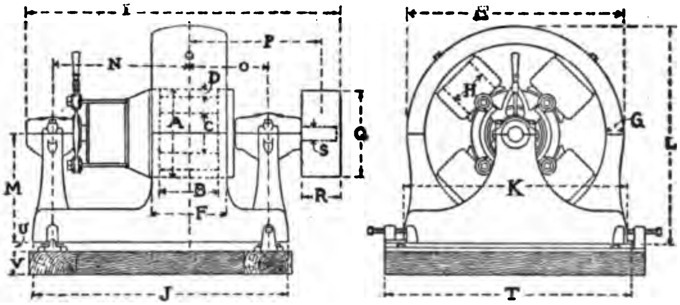

FIG. 10.—GENERAL ELECTRIC FOUR-POLE GENERATOR.

TABLE 8.

DIMENSIONS OF GENERAL ELECTRIC FOUR-POLE MODERATE AND HIGH SPEED RING-ARMATURE GENERATORS.

(See Fig. 10.)

No.	Medium Speed		High Speed.		Weight	Armature.					Magnet Frame.			
	K. W.	R.p.m.	K. W.	R.p.m.	Lbs.	A	B	C	D	No. of Slots.	E	F	G	H
1	6.5	950	9	1450	970	9¼	6	4⅝	.834	46	23⅞	9	$1\frac{13}{16}$	$3\frac{31}{32}$
2	13.5	850	17.5	1175	1810	13	6½	6⅛	.804	52	31	12	$2\frac{3}{16}$	$5\frac{7}{32}$
3	20	700	30	1050	3200	16	7	7⅛	.948	66	37	15	3	6¾
4	30	675	45	975	4780	18	8¾	9¼	.944	116	41	16½	3⅝	$7\frac{5}{16}$
5	50	600	65	875	6930	20¼	8¾	$9\frac{5}{16}$	1 076	98	50	18	3¾	$8\frac{7}{16}$
6	75	550	85	750	8560	22	9¼	10	1.208	96	54	19	4½	9⅛

No.	General Dimensions.								Pulley.			Rails.		Base
	I	J	K	L	M	N	O	P	Q	R	S	T	U	V
1	38	31¾	26	24	12	16½	10¾	16⅛	11	4⅝	1⅜	34¾	1	3
2	49½	39	33	31	15⅛	19⅞	18⅛	21⅝	12½	8⅝	2	43½	1	3
3	60½	45½	40	37	18½	22¾	15¾	26¾	15	10½	2¼	52	1⅝	4
4	67¾	52¾	46½	44½	22½	26⅝	18⅝	29⅞	20½	11	2¾	55	1⅝	4
5	78⅝	57⅝	53	50	25	29¾	18⅞	33⅛	23	18½	3¼	62¾	1¾	6
6	92	63½	56	54	27	31¼	19¾	39	25	24½	3⅞	65½	2	6

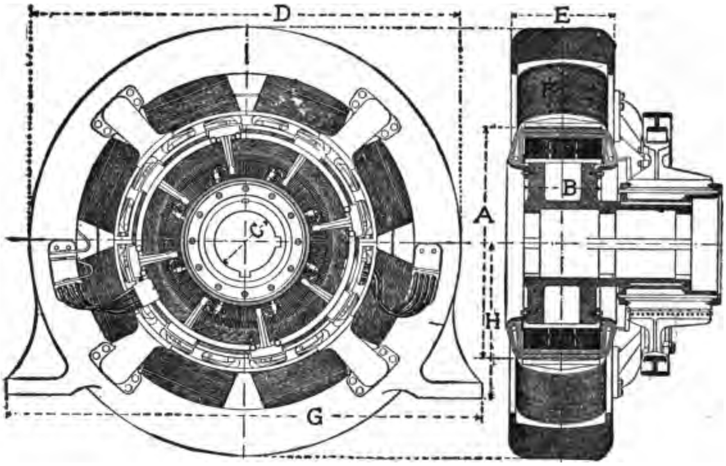

FIG. 11.—CROCKER-WHEELER MULTIPOLAR GENERATOR.

TABLE 9.

DIMENSIONS OF CROCKER-WHEELER MULTIPOLAR LOW, MEDIUM, AND HIGH SPEED SURFACE-WOUND RING-ARMATURE DYNAMOS. (See Fig. 11.)

Low Speed.		Medium Speed.		High Speed.		Nbr. of Poles.	Armature.				Field Frame.				
K. W	R. p. m.	K. W.	R. p. m.	K. W	R. p. m		A	B	C	Nbr. of Slots.	D	E	F	G	H
		2.5	1200	3.5	1600	4	$7\frac{3}{16}$	3⅛	1⅛	40	17⅜	7½	2⅞	17⅜	6¼
		4.5	1150	5.75	1400	4	8⅛	3⅛	1⅛	44	19⅜	8	$3\frac{3}{16}$	19⅜	7¼
		6.5	1050	8.25	1300	4	9⅛		1¼	44	21⅜	8⅛	$3\frac{9}{16}$	21⅜	8¼
		9	950	11.5	1300	4	11	5	1¼	87	25⅛	9¼	4⅛	25⅛	9¼
		13	900	17.5	1300	4	11⅝	6⅝	2	78	28	11⅛	$4\frac{3}{16}$	28	10⅛
2	500					6	12	3½	1½	62	21½	6¼	3⅛	21½	8⅛
		18	875	23	1150	4	13	7	2	99	30⅛	12⅛	4	30⅛	11½
		22.5	850	27	1125	4	14	7⅛	2⅛	78	32¼	13⅛	$4\frac{5}{16}$	32¼	12⅛
4	425					6	15	3½	2	50	25¼	6⅜	3⅛	25¼	9⅛
		30	775	40	1050	4	15	8	2¼	95	36	14⅛	$5\frac{3}{16}$	36	13⅛
		45	700	55	930	4	16⅛	9	3	70	40⅛	15⅛	6½	40⅛	15
7	400					8	19	4½	3	89	30½	8	3⅛	32	12
		65	625	80	750	4	19	10⅛	3⅛	96	48¼	16¼	7¼	48¼	18
9	350					8	21	5	3	73	33¼	8⅛	3⅞	33¼	18
15	325					8	22⅛	6⅛	3½	65	36	11	3¼	40⅝	14¼
20	300					6	20½	6¼	3⅛	76	39½	13⅛	$5\frac{3}{16}$	39⅛	15
30	300					6	22¼	8½	4	109	44¼	13¼	5⅜	44¼	16
50	275	90	560	110	720	6	24	9⅝	4½	141	48⅛	15⅞	6¼	48⅛	18
60	275					6	28	11	4⅛	126	54⅛	17½	6⅛	54⅛	20
75	250	130	500	150	550	6	32⅛	12⅛	6	111	64½	18	7⅞	68	24
		200	450			6	32⅛	13⅛	8	105	68¼	18⅜	$9\frac{3}{16}$	68⅜	25
100	250					8	37	10⅞	6⅛	156	67	17	7¼	68	24
125	250					8	45	13	7	208	76⅜	18	7⅞	80	26
150	130	200	175	250	225	8	50	16⅛	12	108	90	20½	10⅜	99	29⅜
200	100	250	125	300	150	8	57	19	15	168	107	25⅛	14	128	32
		300	100			12	77	14⅛		198	118⅜	23	12		
350	88	400	100	500	125	12	87	15⅜		160	135	25⅛	13⅜		
				6 0	100	12	95	17⅜		152	151	28⅛	15⅜		

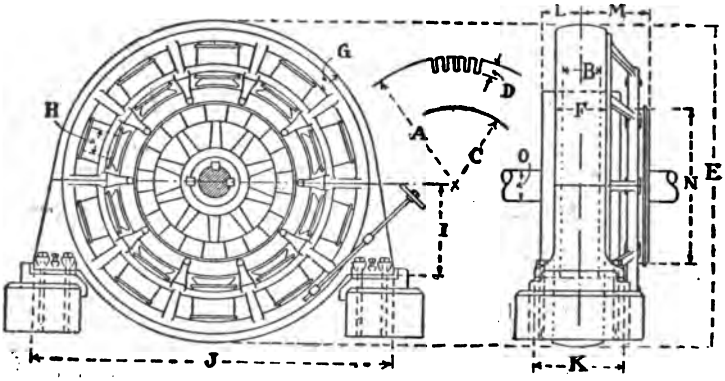

FIG. 12.—GENERAL ELECTRIC MULTIPOLAR GENERATOR.

TABLE 10.

DIMENSIONS OF GENERAL ELECTRIC MULTIPOLAR LOW-SPEED RING-ARMATURE GENERATORS.

(See Fig. 12.)

No.	K. W.	R. p. m.	No. of Poles.	Armature.					Approximate Weight.	
				A	B	C	D	No. of Slots.	Armature and Commutator.	Generator Complete.
1	150	200	6	46	12⅜	26 5/16	1 5/16	130	6400	29000
2	300	150	8	68	14	45	1 27/32	272	17000	55000
3	400	120	8	72	18¼	48	1¾	240	22000	79000
4	500	120	10	84	17¼	62	1¾	280	25000	81000
5	800	80	14	120	19½	98	1¾	364	50000	155000
6	1600	75	22	164	19	144	1¾	440	74000	180000

No.	Magnet Frame.				General Dimensions.						
	E	F	G	H	I	J	K	L	M	N	O
1	99	25	8 11/16	13¾	23	114	35	12⅞	19¾	32	9
2	125	27	10	15¼	32	141	41	16⅛	29⅜	49	11½
3	135	32½	11	18	41	150	48	18 11/16	35 7/16	49	15
4	144½	30	10¾	16¾	44	154	45	17¾	31	60	16
5	187	32	11¾	18	53	201	48	18 5/16	34 5/16	84	19
6	230	24	12⅝	16¾	63	245	48	18⅜	37½	120	24

TABLE 11.

RING-ARMATURE DIMENSIONS.

High Speed.				Medium Speed.				Low Speed.			
K. W.	R.p.m.	Diameter.	Length.	K. W.	R.p.m.	Diameter.	Length.	K. W.	R.p.m.	Diameter.	Length
				.1	1800	3	2				
				.15	1600	3 19/32	1⅝				
				.25	1400	4¾	1⅞				
				.5	1200	5⅝	2⅛				
				1	1000	7	2 3/16				
				1.5	975	7¾	3 5/16				
				2.25	950	8¼	3 9/16	2	500	12	3¼
				2.5	1200	7 3/16	3⅛				
3.5	1600	7 3/16	3⅛	4	925	9 3/16	4 13/16	4	425	15	3¾
				4.5	1150	8½	3⅛				
5.75	1400	8⅛	3⅛	6.5	1050	9¼					
				6.5	950	9¼	6				
				6.5	875	10⅛	5⅝	7	400	19	4¼
8.25	1300	9¼		8.5	850	11	6¼				
9	1450	9¼	6	9	950	11	5	9	350	21	5
11.5	1300	11	5	13	900	11⅝	6⅝				
17.5	1300	11⅝	6⅝	13.5	850	13	6½	15	325	22½	6½
17.5	1175	13	6½	18	875	13	7				
23	1150	13	7	20	700	16	7	20	300	20¼	6¾
27	1125	14	7½	22.5	850	14	7½				
30	1050	16	7	30	775	15	8	30	300	22¼	8¼
40	1050	15	8	30	675	18	8¾				
45	975	18	8¾	45	700	16½	9	50	275	24	9⅝
55	930	16½	9	50	600	20¼	8¾	60	275	28	11
65	875	20¼	8¾	65	625	19	10½	75	250	32½	12½
80	750	19	10½	75	550	22	9¼	100	250	37	10⅞
85	750	22	9¼	90	560	24	9⅝	125	250	45	13
110	720	24	9⅝	130	500	32½	12½	150	200	46	12⅝
150	550	32½	12½					150	130	50	16½
200	450	32½	13½	200	375	50	16½	200	100	57	19
				250	225	50	16½	250	125	57	19
								300	150	57	19
								300	150	68	14
								300	100	77	14½
								350	88	87	15¾
								400	120	72	18¼
								400	100	87	15¾
								500	125	87	16¾
								500	120	84	17¼
								600	100	95	17¾
								800	80	120	19½
								1600	75	164	19

TABLE 12.

DRUM-ARMATURE DIMENSIONS.

High Speed.				Medium Speed.				Low Speed.			
K. W.	R. p. m.	Dia.	Length.	K. W.	R. p. m	Dia.	Length.	K. W.	R. p. m.	Dia.	Length
.5	2400	2 5/16	4					.56	1300	5 3/4	2 5/8
.75	2400	2 5/8	5	.75	1900	5 3/4	2 5/8	1.5	1200	6 1/2	3 1/4
1.5	2100	3 13/16	6 1/2	1.875	1700	6 1/4	3 1/4	2.62	1050	7 3/4	4 5/8
3	1900	4 1/2	8	3.75	1600	7 3/4	4 5/8	3.75	950	8 1/2	5 1/2
6	1800	5 11/16	9 1/4	5.62	1350	8 1/2	5 1/4	5.62	850	9 1/8	5 1/2
8.5	1700	5 7/8	10	7.5	1250	9 1/2	5 1/2	7.5	750	10 1/2	6
12	1600	6 1/2	12	11.25	1150	10 1/2	6	11.25	650	11 5/8	6 3/4
15	1500	6 3/4	13 1/2	15	1050	11 5/8	6 3/4	15	600	13	8
20	1400	7 3/4	15	22.5	975	13	8	22.5	575	15	8 1/2
25	1300	8 3/4	16 1/2	30	950	13 7/8	8 1/4	30	550	15 3/8	8 1/2
30	1200	9 3/16	18	37.5	900	15	8 1/2	37.5	550	16 1/2	9
45	1000	11 1/16	20 1/2	45	850	15 3/4	8 1/4				
56.25	800	16 1/8	9								
60	700	12 7/8	24 1/2								
100	650	16 5/8	25								
150	450	28 3/4	26 1/2								
200	450	28 1/2	34 1/2								

It will be noted in Tables **11** and **12**, where machines of different manufacturers are placed side by side, that the armature dimensions of dynamos for similar output and speed in some instances vary greatly from one another, which goes to show that a wide range is given to the judgment of the designer in assuming the variable quantities such as peripheral speed, shape-ratios, etc. For instance, in Table **11** two *300 K. W. 150 revolution* armatures are given, the first having a diameter of 57 inches and a length of 19 inches, while the second has a diameter of 68 inches and a length of 14 inches. The peripheral velocity in the first machine is $v = \frac{57 \times \pi}{12} \times 150 = 2240$ feet p. min., while in the second it is $\frac{68 \times \pi}{12} \times 150 = 2670$ feet p. min. The length is $\frac{19}{57}$, or $\frac{1}{3}$ of the diameter in the first armature, and $\frac{14}{68}$, or about $\frac{1}{5}$ of the diameter in the second armature.

20. Specific Cross-Section of Armature Conductors.—It is customary to allow from 300 to 1,000 circular mils per ampere in armature conductors. The lower value applies to elevator motors and other machines that are used only intermittently, and seldom at full load, while the higher limit is for large machines running heavily loaded for long periods of time. An ordinary figure is 600 circular mils per ampere, which corresponds to a current density of about 2,000 amperes per square inch of cross-section.

One should be especially careful to determine correctly what fraction of the total current each conductor will have to carry, as follows:

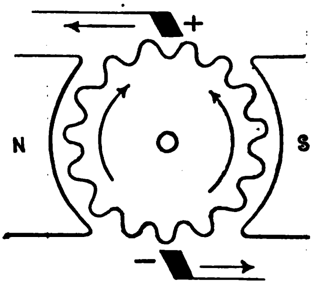

FIG. 13.—FLOW OF CURRENT IN BIPOLAR ARMATURE.

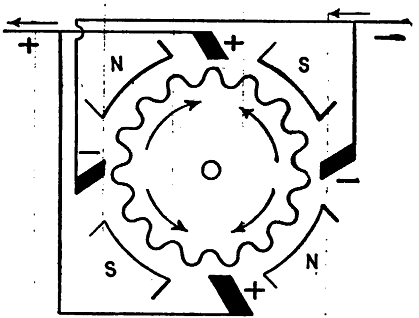

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FIG. 14.—FLOW OF CURRENT IN MULTIPOLAR ARMATURE.

1. In a *bipolar* machine there are *two* paths through the armature winding (Fig. 13), so that one-half of the total current flows through any given inductor.
2. In a *multipolar* machine with the + and − brushes respectively connected in parallel (Fig. 14), or with cross-connected armature winding or commutator (Fig. 15, page 27), there are as many paths as there are poles, consequently the current in any conductor is the total amount divided by the number of poles.
3. In a *multipolar* machine the armature is sometimes

wound so that there are only two paths through it, being called a *two-circuit* winding (Fig. 16, page 27).

4. In *bipolar* or *multipolar* machines *two or more conductors* are often used in *parallel* to avoid the trouble of handling large wires, or in order to fit them into a certain space.

TABLE 13.

DATA OF BARE AND DOUBLE COTTON-COVERED WIRE

1	2	3	4	5	6	7	8	9
Size. B. & S.	Diam., inches, Bare Wire.	Area, Circular Mils. Bare Wire.	Lbs. per foot, Bare Wire.	Ohms per ft. at 20° C.	Max. Diam. of D. C. C. Wire.	Number of wires per inch. D. C. C.	Number of wires per square inch. D. C. C.	Resistance per cubic inch at 20° C. D. C. C.
5	.1819	33,124.	.1002	.000813	.197	5.1	25.8	.000673
6	.1620	26.244.	.0795	.000394	.177	5.6	31.9	.0010 0
7	.1443	20,736.	.0630	.000497	.159	6.3	39.6	.001638
8	.1285	16,384.	.0500	.000627	.143	7.0	48.9	.00256
9	.1144	12,996.	.0396	.000791	.129	7.8	60.2	.00396
10	.1019	10,404.	.0314	.000992	.117	8.5	78.1	.00607
11	.09074	8,281.	.0249	.00126	.106	9.4	89.0	.00934
12	.08081	6,561.	.0198	.00159	.093	10.8	115.6	.01526
13	.07196	5,184.	.0157	.00200	.084	12.0	145.2	.02410
14	.06408	4.096.	.0124	.00252	.075	13.3	177.8	.0373
15	.05707	3,249.	.0099	.00318	.067	14.9	222.8	.0590
16	.05082	2,601.	.0078	.00401	.061	16.4	268.7	.0896
17	.04526	2,025.	.0062	.00506	.055	18.2	330.6	.1392
18	.04030	1,600.	.0049	.00638	.050	20.0	400.0	.2124
19	.03589	1,296	.0039	.00804	.046	21.7	473.5	.3172
20	.03196	1,024.	.0031	.01014	.042	23.8	566.9	.4790
21	.02846	812.3	.00245	.01275	.038	26.3	692.5	.7375
22	.02536	640.1	.00195	.01608	.035	28.6	876.3	1.0963
23	.02257	510.8	.00154	.02030	.033	30.3	918.3	1.555
24	.02010	404.	.00122	.02560	.030	33.3	1111.1	2.373
25	.01790	320.4	.00097	.03225	.028	35.7	1276.4	3.436
26	.01594	252.8	.00077	.04075	.026	38.5	1479.3	5.022

21. Data for Armature Winding.—The data given in the above Table **13** will be found useful by the student when calculating an armature. The table gives the area, diameter, specific weight, specific resistance, the number of wires that can be wound in a given space, and the resistance per cubic inch of winding for the sizes usually employed for generator and motor armatures. Columns *6* to *9* refer to Double Cotton-Covered (D. C. C.) wire, this being the kind of insulation usually employed on conductors for armature winding. Wires larger than No. 5 B. & S. are commonly not used, on account of the greater difficulty of handling and winding; if a larger area than 33,000 circular mils is required, two wires of one-half, or three wires of one-third the requisite cross-section, etc., are used.

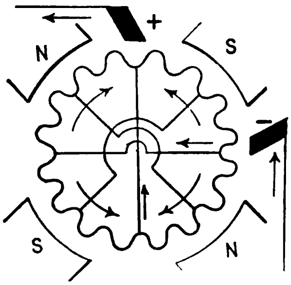

FIG. 15.—FLOW OF CURRENT IN CROSS CONNECTED MULTIPOLAR ARMATURE.

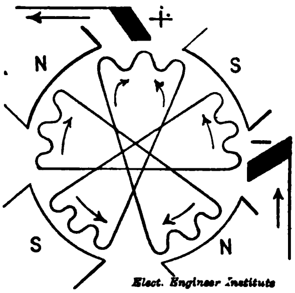

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FIG. 16.—FLOW OF CURRENT IN MULTIPOLAR TWO-CIRCUIT WINDING.

22. Examples showing Use of Winding Table.—The use of the various data given in Table **13** is seen from the following example. Suppose an *18×25* inch smooth drum armature is wound to a height of about .6 inch with No. *5* B. & S. wire, this size being determined, as shown in Pars. **23** to **25**, by finding the requisite cross-section for the current to be carried and comparing the result with the figures given in the third column of Table **13**.

The periphery of the armature is $18 \times \pi = 56.55$ inches; hence, by column 7, the number of wires per layer, when allowing 8 per cent. of the armature circumference for division strips and spaces, is $56.55 \times .92 \times 5.1 = 265$. The number of layers is $.6 \times 5.1 = 3$; hence there are, in all, $265 \times 3 = 795$ wires on the armature.

The latter result can also be obtained approximately from column *8*, thus: 56.55 × .92 × .6 × 25.8 = *805* wires, which is a few per cent. in excess of the actual value, owing to the use of .6 instead of 3 × .197 = .591 as the height of the winding space.

The length of one complete turn on this armature is about 9 feet, and includes 2 wires; consequently the weight of wire, by column *4*, is $\frac{795}{2} \times 9 \times .1002 = 358$ lbs., and its total resistance, all in series, at 20° C., by column *5*, is $\frac{795}{2} \times 9 \times .000313 = 1.12$ ohm.

The resistance can also be obtained in the following manner: The cubical contents of the winding space is 56.55 × .591 × 25 = 835 cubic inches. Doubling this figure, to allow for the heads and commutator connections, we have, from column *9*: 835 × 2 × .000673 = *1.124* ohm as the approximate total resistance R_a of the wire on the armature (see Par. **39**).

23. Approximate Size of Armature Conductors.—It follows from Par. **20** that the approximate cross-section of the armature conductor for a given case is found by multiplying the current flowing through it by the specific cross-section suited for that case. Having in this manner found the number of circular mils of area required, the size of the wire is taken from column *3*, Table **13.**

24. Example of Bipolar Armature.—*What size of conductor will be required on the armature of a* **5 H. P.** *bipolar motor for* **110**-*volt circuit?*

Solution.—5 H. P. is equivalent to 5 × 746 = 3,730 watts output. Assuming 85% efficiency as a fair value for this size, the watts input are 3,730 ÷ .85 = 4,388 watts. The current is 4,388 ÷ 110 = 40 amperes, hence each conductor must carry one-half of 40, or 20 amperes, which at 600 circular mils per ampere requires a wire of 12,000 cir. mils. Referring to Table **13,** the nearest size is found to be No. 9 B. & S., having a cross-section of 12,996 cir. mils.

25. Example of Multipolar Armature.—*Find the approximate size of armature conductor for a* **200-K. W.,** **6**-*pole,* **550**-*volt railway generator.*

Solution.—The total current will be 200 × 1,000 ÷ 550 = 364 amperes, which will be divided between six paths if the armature is cross-connected, each conductor carrying 364 ÷ 6 = 61 amperes, and requiring a cross section of 61 × 600 = *36,600* C. M. The nearest larger size of wire is *No. 4* with 41,616 C. M. If it be desired to subdivide this in order to facilitate winding or placing in a certain size of slot, it is possible to substitute *two No. 7* wires in parallel, having a combined cross-section of 41,472 C. M. For a two-circuit winding, each conductor would have to carry one-half the total current, or 182 amperes, requiring a cross-section of 182 × 600 = *109,200* C. M., which is somewhat larger than a *No. 0* wire (105,625 C. M.) This would be still more clumsy to handle, and might be replaced by *two No. 3* or by *four No. 6* wires in parallel.

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THE DESIGN OF DIRECT-CURRENT DYNAMOS AND MOTORS.

FINAL CALCULATION OF ARMATURE.

26. Number of Inductors on Armature.—The size of the inductors having been ascertained, the designer may proceed to determine the number of them that can be properly placed upon the armature core, the approximate size of which has been computed. The number of inductors that can be placed upon the circumference of a smooth core, or into the slots of a toothed armature, depends upon the height to which it is expedient to wind the armature, this height, in a toothed core, corresponding to the depth of the slots. The height of the armature winding, h_a (Figs. 17 and 18, page 45), varies with the type and size of the armature, and can be taken approximately from Table **14**, which gives average values for various cases.

The total winding space, S_w, of a *smooth-core armature* is roughly given by the following formula, provided that h_a is very small compared with D_a, which is practically always the case:

$$S_w = D_a\pi \times h_a \ldots\ldots\ldots\ldots\ldots\ldots \mathbf{(14)}$$

In ordinary smooth-core machines, from $\frac{2}{5}$ to $\frac{1}{2}$ of this total winding space is occupied by insulation, division strips, binding bands, etc., hence the available inductor space is:

$$S_w' = .55 S_w = .55 D_a\pi \times h_a = 1.75 \times D_a \times h_a \ldots \mathbf{(15)}$$

The number of inductors on the armature is the inductor space, S_w', divided by the space occupied by one inductor. Calling the diameter of the bare inductor d_a, each inductor takes up the space d_a^2. The approximate total number of inductors, N, on a smooth-core armature can therefore be obtained from:

$$N = \frac{S_w'}{d_a^2} = 1.75 \times \frac{D_a \times h_a}{d_a^2} \ldots\ldots\ldots\ldots (16)$$

In *toothed armatures,* the slots usually take up about one-half of the circumference, and only about three-fifths, or .6, of the total slot area is actually occupied by the inductors, approximately one-fifth of the slot area being used up by the slot lining and about one fifth of it by the wire insulation. Hence, the approximate total number of inductors is:

$$N = \frac{.5 \times .6 S_w}{d_a^2} = \frac{.3 \times D_a \pi \times h_a}{d_a^2} = \frac{D_a \times h_a}{d_a^2} \ldots (17)$$

The figures obtained by (**16**) and (**17**) should be checked by means of Table **13**, as shown in Par. **22**.

TABLE 14.

AVERAGE HEIGHT OF WINDING SPACE ON ARMATURES.

Diameter of Armature, in Inches. D_a.	Approximate Height of Winding Space, h_a.		
	Smooth Armature Core.		Toothed Armature.
	Drum.	Ring.	
2″	$\frac{1}{4}$″	..	..
4	$\frac{5}{16}$	$\frac{7}{32}$″	..
6	$\frac{3}{8}$	$\frac{1}{4}$	$\frac{5}{8}$″
10	$\frac{1}{2}$	$\frac{9}{32}$	$\frac{3}{4}$
15	$\frac{5}{8}$	$\frac{5}{16}$	1
20	$\frac{3}{4}$	$\frac{3}{8}$	$1\frac{1}{4}$
30	$\frac{7}{8}$	$\frac{7}{16}$	$1\frac{1}{2}$
50	..	$\frac{1}{2}$	$1\frac{3}{4}$
75	..	$\frac{5}{8}$	2
100	..	$\frac{3}{4}$	$2\frac{1}{2}$
150	..	$\frac{7}{8}$	$3\frac{1}{4}$
200	..	1	4

27. Arrangement of Inductors on Smooth-Core Armature.—The number of inductors found by formula (**16**) must be modified according to the number of divisions and to the manner of winding of the armature. The number of divisions of a smooth-core armature is either equal to, or twice, the number of commutator segments, the latter depending upon the voltage and on the number of poles of the machine. For machines up to *300* volts, the commutator is usually divided into from *40* to *60* segments per pair of poles. For higher potentials, a correspondingly greater number of segments is provided; thus, for *500* volts up to *100* segments, and for *1,000* volts up to *150* segments, per pair of poles are used.

In a smooth armature, the number of wires per layer must be a whole multiple of the number of armature divisions; to find the final number of wires per layer, therefore, multiply the circumference of the armature (diminished by the space allowed for division strips) by the number of wires per inch (column 7, Table **13**); divide the result by the number of commutator segments, and note the quotient so obtained. If this quotient is not quite a whole number, but so nearly so, that the deficiency can be made up by a moderate reduction of the allowance made for division strips, the number per layer is the product of the raised quotient by the number of commutator segments. If the quotient is but little greater than a whole number, the number of wires per layer is the next smaller whole number multiplied by the number of commutator segments. If the quotient is not sufficiently near a whole number to allow one or the other of the above methods to be employed, either the next smaller or the next larger whole number must be taken and the number of commutator segments so adjusted that the product of the two numbers is equal to, or slightly less than, the number of wires previously obtained by multiplying the available circumference by the number of wires per inch.

The corrected number of wires per layer is then multiplied by the number of layers, which, in turn, is found by multiplying the height of the winding space by the number of wires per inch and rounding the result to the next smaller whole number.

In case of but a few layers of heavy wire, if the calculated number of layers is a considerable fraction above a whole number, it is even advisable to replace the armature conductor by two or more wires of equivalent total cross-section, and to re-design the arrangement of the armature winding so that the permissible winding space is made use of more economically.

The actual total number of inductors on the armature is then the number of armature divisions times the number of wires per division, divided by the number of wires employed in subdividing the area of the armature conductor.

28. Arrangement of Wires on Toothed Armature.

—The number of slots of a toothed armature is governed by its size, the usual limits of the slot numbers for various sizes of toothed armatures being given in Table **15,** for reference.

TABLE 15.

NUMBER OF SLOTS IN TOOTHED ARMATURES.

Diameter of Armature.	Number of Slots.
5 inches.	25 to 40
10 "	30 " 60
15 "	40 " 80
20 "	60 " 100
30 "	80 " 150
50 "	100 " 200
100 "	150 " 300
150 "	200 " 400

Dividing the total number of wires, obtained from formula (**17**), by the number of slots, taken from Table **15**, the number of wires per slot is obtained. The latter must be such that the slot is evenly filled with the winding; that is to say, the slot must contain a proper number of full layers nearly filling the space within the slot lining. If this condition is not obtained by the first selection of the slot number, a second, and eventually a third, must be chosen within the given limits, and, if necessary, even the size of conductor must be changed by suitable subdivision of the cross-section.

It usually happens, in case of smooth as well as of toothed armatures, that a particular size of wire will not suit a certain case, and it is often very difficult to find any regular size that will fit exactly right. In fact, it is a large part of the work of designing a machine to make these relations come out satisfactorily. If necessary, a special size of wire can be made to order, but this should be done only as a last resort.

29. Example of Smooth-Core Armature.—*How many No.* **6** *B. & S. wires can be wound upon a smooth-core drum armature* **10** *inches in diameter?*

Solution.—Here $D_a = 10''$; $d_a = .162''$, $d_a^2 = .026244$ (compare with column *3* of Table **13**); and from Table **14** we find that the average winding depth for this size of armature is about *.5* inch; hence, by formula (**16**):

$$N = \frac{1.75 \times 10 \times .5}{.026244} = \mathbf{332} \text{ wires.}$$

In order to verify this result, we find in Table **13** that the diameter of No. *6* B. & S. wire, including its double cotton covering, which is almost always used for armature winding, is *.177* inch. The circumference of the armature is $10 \times \pi = 31.416$ inches, *90* per cent. of which, or *28.27* inches, is occupied by the winding; hence, the number of wires per layer is $28.27 \div .177 = 160$.

The core insulation and binding in an armature of the size under consideration will amount to a height of about $\frac{1}{8}$ inch; hence, the number of layers that can be placed on this armature is $\frac{.5 - \frac{1}{8}}{.177} = 2$, and the total number of inductors, therefore, $160 \times 2 = 320$, which agrees very well with the result obtained by formula (**16**).

Assuming that a commutator of *54* divisions is to be used with this armature, the number of conductors must be modified as follows: Number of wires per layer of armature section is 160 ÷ 54 = 2.96; taking *3* wires, we have *54* × *3* = *162* wires per layer; and since there are *2* layers, the actual number of wires on this armature will be *162* × *2* = **324**, or 2 × 3 = 6 wires per commutator division.

30. Example of Toothed Armature.—*Find the approximate number of No.* **9** *B. & S. wires that can be placed on a toothed armature having a diameter of* **18** *inches.*

In this case $D_a = 18''$, $h_a = 1.15$ (by interpolation from Table **14**), and $d_a^2 = .013$, nearly, (from Table **13**); therefore, by formula (**17**):

$$N = \frac{18 \times 1.15}{.013} = \mathbf{1590} \text{ wires.}$$

This result may be checked as follows: The circumference of the armature under consideration is *18* × π = *56.55* ins., about one-half of which, or *28.3* ins., is occupied by the slots. The slots being *1.15* inch deep, the total slot area is *28.3* × *1.15* = *32.5* square inches. Of this area, only about four-fifths is actually occupied by the conductor, including its own cotton covering; hence, the effective slot area is *32.5* × $\frac{4}{5}$ = *26* square inches.

According to Table **13**, the number of No. *9* wires, D. C. C., which can be wound in one square inch is *60.23*; consequently we have *26* × *60.23* = **1566** as the total number of conductors, which agrees with the above result obtained by formula (**17**).

According to Table **15**, the average number of slots for an armature of the size considered is about *80*; hence, the number of wires per slot is *1590* ÷ *80* = *20*. The width of the slot is the available circumference divided by the slot number, or *28.3* ÷ *80* = *.35* inch, while its depth, h_a, is *1.15*. Deducting $\frac{1}{32}$ inch for lining of the sides and the bottom of the slot, the available depth of the slot becomes $1.15 - .031 = 1.119$ inch, and the available width $.35 - (2 \times .031) = .288$ inch.

The diameter of No. *9* D. C. C. wire is *.129* inch; the depth of the slot will therefore take $1.119 \div .129 = 9$ wires, and the width will take $.288 \div .129 = 2$ wires, giving a total of *18* wires per slot. In order to accommodate *9* wires in height, the depth of the slot must be slightly increased, the size required being $(9 \times .129) + .031 = 1.2$ inch. On the other hand, the width of the slot is not completely filled by the *2* wires, hence a more economical arrangement will be obtained by using a correspondingly greater number of narrower slots.

The width required for 2 wires and 2 slot insulations is $2 \times (.129 + .031) = .32$; hence, we may have $\frac{(.35 - .32) \times 80}{.32} = 7.5$ additional slots. Taking *8*, the nearest even whole number, the corrected number of slots is $80 + 8 = 88$, and the total number of wires that can actually be placed on the armature is $88 \times 18 =$ **1584.**

31. Approximate Length of Active Armature Inductor.

31. Approximate Length of Active Armature Inductor.—The length of armature inductor required to generate a given E. M. F. can be computed from the fundamental fact that 1 volt E. M. F. in a generator, or counter E. M. F. in a motor, is generated when lines of force are cut at the rate of *100,000,000*, or 10^8, lines per second.

Accordingly, each foot of inductor, when moving at the rate of *1* foot per minute in a magnetic field having a density of *1* line per square inch, since it moves across 1 square foot (= 144 square inches) of field, and therefore cuts *144* lines of force per minute, or $144 \div 60 = 2.4$ lines per second, generates

$$\frac{2.4}{100{,}000{,}000}, \text{ or } 2.4 \times 10^{-8} \text{ volt.}$$

If there are l_a feet of inductor on the armature, the voltage generated is l_a times as great as that produced by *1* foot of inductor. If the armature revolves with a velocity of v feet per minute, the voltage generated is v times as great as when moving at the rate of *1* foot per minute. If the magnetic density in the air gaps is $\mathbf{B}_g$ lines per square inch, the voltage is $\mathbf{B}_g$ times that for a field density of *1* line per square inch. On account of the fact that the polepieces do not completely surround the armature, not all of the inductors are cutting lines at the same time. The number of *idle* inductors usually varies from *15* to *25* per cent., and averages about *17* per cent.; hence, the *effective* length of the inductors is 100 − 17 = *83* per cent., or *.83* of the total length of inductors. If the armature winding consists of n_p pairs of parallel branches, the voltage generated by the $.83 l_a$ feet of useful inductors must be divided by $2n_p$, since the total voltage is generated in each of the $2n_p$ branch circuits. The total E M. F. generated in an armature is therefore given by the formula:

$$E = 2.4 \times 10^{-8} \times \frac{.83 \times l_a \times v \times \mathbf{B}_g}{2n_p} = \frac{l_a \times v \times \mathbf{B}_g \times 10^{-8}}{n_p}, \ldots (18)$$

from which the length of the armature inductor required to generate the voltage E is found, in feet:

$$l_a = \frac{E \times n_p \times 10^8}{v \times \mathbf{B}_g} \ldots\ldots\ldots\ldots\ldots\ldots (19)$$

The E. M. F., E and the number of *bifurcations*, or pairs of armature circuits, n_p, being given, the fitness of the result depends upon the correct assumption of the velocity, v, and of the field density, $\mathbf{B}_g$. The former has already been discussed in Par. **14,** the latter is treated in Par. **32.**

32. Field Density.—The density of the magnetic field, or the *gap induction*, as it is sometimes called, must be properly chosen according to the size of the machine, the number of poles, the form of the armature, and the material of the polepieces. In general, the density is taken the higher, the larger the output of the machine, and the greater the number of poles. In dynamos with smooth-core armatures, the densities are made greater than in those with toothed cores; and in a machine having wrought iron or steel polepieces, the density can be chosen about *50* per cent. higher than in a similar machine with cast iron poles.

Suitable average values of $\mathbf{B}_g$ for ordinary dynamos and motors are given in Table **16.**

TABLE 16.

AVERAGE FIELD DENSITIES FOR DYNAMOS AND MOTORS, IN LINES PER SQUARE INCH.

Capacity in K. W.	Bipolar Dynamos.				Multipolar Dynamos.			
	Smooth Armature.		Toothed Armature.		Smooth Armature.		Toothed Armature.	
	Cast Iron Pole-pieces.	Steel Pole-pieces.	Cast Iron Pole-pieces.	Steel Pole-pieces.	Cast Iron Pole-pieces.	Steel Pole-pieces.	Cast Iron Pole-pieces.	Steel Pole-pieces
.1	10000	15000	8000	12000	14000	20000	12000	18000
.25	12000	18000	10000	15000	16000	24000	14000	21000
.5	14000	20000	12000	18000	18000	27000	16000	24000
1	15000	22000	13000	19000	19000	28000	17000	25000
2.5	16000	24000	14000	20000	20000	29000	18000	26000
5	17000	25000	15000	22000	21000	30000	19000	28000
7.5	18000	26000	16000	24000	22000	32000	20000	30000
10	19000	28000	17000	25000	24000	35000	21000	32000
25	20000	30000	18000	27000	26000	38000	22000	35000
50	22000	33000	20000	30000	28000	41000	23000	38000
100	24000	36000	22000	33000	30000	44000	25000	40000
200	27000	40000	24000	36000	32000	47000	27000	42000
300	30000	45000	27000	40000	35000	50000	29000	44000
500	....	....	....	....	38000	53000	31000	46000
1000	....	....	....	....	41000	56000	33000	48000
2000	....	....	....	...	45000	60000	35000	50000

If a strong magnetic field is desired for the purpose of preventing, or diminishing, the distorting effect of armature reaction, values of the gap induction about *20* to *30* per cent. in excess of those given in the above table are usually taken.

For machines having a very low voltage, such as *electroplating machines, battery motors*, etc., or for generators in which the amperage is relatively very high, as in *incandescent generators of large outputs*, the field density is usually taken about two-thirds or three-fourths of the density employed under similar conditions for ordinary machines.

33. Length of Armature Core.—Having computed the required length of active wire, l_a, from (**19**), while the number of inductors, N, has been found in accordance with Pars. **26** to **30**, the length of the armature core, L_a, in inches, may be obtained by dividing the length of active wire, expressed in inches, by the number N, or in symbols:

$$L_a = \frac{12\, l_a}{N} \ldots\ldots\ldots\ldots\ldots\ldots (20)$$

The above method of obtaining the length of the armature by finding the length of active wire, necessitates the assumption of the field density. Another plan is to compute the total flux from the number of inductors, as will be shown in Par. **34**, and to adjust the length of the armature so that the final density attains a proper value. The latter method is simpler, because it is independent of exact dimensions and involves only total values.

34. Preliminary Determination of Flux in Armature.—With a given number of inductors, N, the total flux, Φ, passing through the armature must be such as to give E, the E. M. F. generated, at the specified number of revolutions per minute, n_1. Remembering that the lines of flux are cut twice per revolution by each inductor, and that the number of inductors in series to generate E volts is $\frac{N}{2n_p}$, when n_p denotes the number of pairs of parallel branches in the armature, we have:

$$E = 2\Phi \times \frac{N}{2n_p} \times \frac{n_1}{60} \times 10^{-8} \text{ volts,}$$

from which $\Phi = \frac{60 \times 10^8 \times 2n_p \times E}{2 \times N \times n_1} = \frac{6 \times 10^9 \times n_p \times E}{N \times n_1}$ ...(**21**)

The value of Φ can also be found when the flux density, $\mathbf{B}_g$, in the air gap, the length, L_a, of the armature, and its diameter, D_a, are known. If in this case the average percentage of the idle inductors is taken as *17*, see Par. **31,** the flux in the armature is obtained as follows:

$$\Phi = \tfrac{1}{2}\mathbf{B}_g \times .83 D_a \pi \times L_a = 1.3 \times \mathbf{B}_g \times D_a \times L_a \ldots(\mathbf{22})$$

If $\mathbf{B}_g$ is not given, it may be assumed from Table **16.** As stated in Par. **33,** however, this indirect method is not as satisfactory as the direct method represented in (**21**), but it may be used as a check on the latter.

Equations (**21**) and (**22**) apply to multipolar as well as to bipolar machines. In case of *bipolar* dynamos the total flux, Φ, in the armature is the number of lines which enter it from the polepiece of North polarity, while in a *multipolar* field it is the *sum* of the lines that enter it from *all* of the North poles. The same lines pass out through the South pole-faces; hence, Φ is one-half of all the lines entering and leaving the armature. For this reason, the factor *2* is used in (**21**), and the factor ½ in (**22**). The student should be careful to avoid confusion on this point, especially as the flux per pole and the flux per magnetic circuit are often used in calculations, instead of the total flux.

Before the flux Φ is computed by (**21**) or (**22**), the approximate size of the armature should be determined by the methods given in Pars. **13** to **18,** otherwise the resulting flux density in the armature core might either be absurdly high, that is, above the practical magnetic saturation point, or else far below the normal value. It must be borne in mind that all of these preliminary calculations are tentative, the object being to reconcile and adjust the various elements, so that in the end a harmonious result will be obtained.

35. Example.—*The armature of a bipolar ring dynamo is required to generate* **10** *kilowatts at* **120** *volts when running at* **350** *revolutions per minute, the total number of armature inductors being* **400.** *What should be the total flux through the armature?*

Solution.—In bipolar dynamos, according to Par. **20,** there are *2* paths for the current in the armature; hence, n_p, the number of pairs of parallel branches, is *1*, and we have from (**21**):

$$\Phi = \frac{6 \times 10^9 \times 120}{400 \times 350} = \mathbf{5{,}140{,}000} \text{ lines of force.}$$

By (**6**) the given armature has a diameter of about

$$D_a = 3.8 \times \frac{2000}{350} = 21.7 \text{ inches.}$$

Inserting this value into formula (**13**), we have

$$21.7 = \sqrt{\frac{s \times k \times W}{2\pi \times (1 - m') \times (m + m')}}.$$

In the present case $W = 10{,}000$ watts. Taking $s = 1$ (Par. **16**), $k = .12$ (Table **3**), and assuming $m' = .10$ (Table **4**), the above equation becomes:

$$21.7^2 = \frac{1 \times .12 \times 10\,000}{6.28 \times (1 - .10) \times (m + .10)}$$
$$= \frac{1200}{(6.28 \times .90 \times m) + (6.28 \times .90 \times .10)};$$

from which follows:

$$m = \frac{1200 - (21.7^2 \times 6.28 \times .90 \times .10)}{21.7^2 \times 6.28 \times .90} = \frac{934}{2660} = .35.$$

The approximate length of the armature is, therefore:

$$L_a = .35 \times 21.7 = 7.6 \text{ inches.}$$

From Table **16,** the proper value of the field density, for cast steel poles, is found to be $\mathbf{B}_g = 28{,}000$ lines per sq. in.; hence by (**22**):

$\Phi = 1.3 \times 28{,}000 \times 21.7 \times 7.6 = \mathbf{6{,}000{,}000}$ lines of force, which shows that the result obtained by (**18**) is practical.

36. Radial Depth of Armature Core.—The cross-section of the armature core must be made of sufficient area to carry the flux Φ given by (**21**) without over saturation of the iron and without causing excessive power losses due to hysteresis and eddy currents. The length, L_a, of the core having been determined by (**20**), the radial thickness of the armature core, B_a, is obtained thus:

$$B_a = \frac{\Phi}{2n_p \times L_a \times \mathbf{B}_a}, \dots\dots\dots\dots\dots (23)$$

where n_p is the number of pairs of magnet poles, and $\mathbf{B}_a$ the flux density in the armature. The latter should be chosen within the limits given in Table **17**.

TABLE 17.

FLUX DENSITIES IN ARMATURE CORE.

Kind of Machine.	Flux Density in Armature.
Ordinary Bipolar Dynamos and Motors...............	60,000 to 90,000 lines p. sq. in.
Ordinary Multipolar Dynamos and Motors..........	50,000 " 70,000 " " "
Arc Lighting Machines....	100,000 " 130,000 " " "
Dynamos for Plating, Accumulator-Charging, etc., and Battery Motors	30,000 " 50,000 " " "
Alternators.......	20,000 " 40,000 " " "

37. Example.—*Find the radial depth of a smooth-core ring armature of* **45** *inches diameter, having* **1,200** *inductors and generating* **550** *volts when revolving at a speed of* **200** *revolutions per minute in a* **6**-*pole field having a density of* **40,000** *lines per square inch.*

Solution.—From formula (**5**) we have

$$v = \frac{45 \times 200}{3.8} = 2{,}360 \text{ ft. p. min.};$$

therefore, by **(19)**:

$$l_a = \frac{550 \times 3 \times 10^8}{2,360 \times 40,000} = \mathit{1,750} \text{ feet,}$$

and by **(20)**:

$$L_a = \frac{12 \times 1,750}{1,200} = \mathit{17.5} \text{ inches.}$$

The total flux is obtained from **(21)**, thus:

$$\Phi = \frac{6 \times 10^9 \times 3 \times 550}{1,200 \times 200} \ \mathit{41,200,000} \text{ lines of force.}$$

Taking the average value of $\mathbf{B}_a$ for multipolar dynamos given in Table **17**, namely $\mathbf{B}_a = 60,000$, the required radial depth is found by formula **(23)**:

$$B_a = \frac{41,200,000}{6 \times 17.5 \times 60,000} = \mathbf{6.5} \text{ inches.}$$

Subtracting twice this depth from the external diameter, the internal diameter of the given armature is found to be 45 – 13 = *32* inches.

38. Total Length of Armature Conductor.—The active or inductive length, l_a, of the armature conductor being known by **(19)**, the total length of wire on the armature may be obtained approximately by making due allowances for the inactive length required to join the active portions of the armature conductors into continuous turns, or convolutions.

In a *drum armature* the total length of wire, l_A, depends upon the ratio of diameter to length of armature core and is given approximately, in feet, by the formula:

$$l_A = l_a \times \left(1 + \frac{k \times D_a}{L_a}\right) \dots\dots\dots\dots \mathbf{(24)}$$

Since the total active length is more accurately obtained by multiplying the number of conductors by the active length of one conductor, formula **(24)** can also be written in the form

$$l_A = N \times \frac{L_a}{12} \times \left(1 + \frac{k \times D_a}{L_a}\right) = \frac{N}{12}\left[L_a + (k \times D_a)\right], \dots \mathbf{(25)}$$

in which k is a constant varying between the following values, according to the diameter of the armature and to the height of the winding space, the average length of a convolution (Fig. 17) being the greater, the larger the area of the shaft and that of the winding space as compared with the end-surface of the armature core:

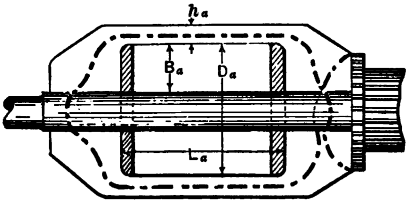


FIG. 17.—CONVOLUTION ON DRUM ARMATURE.

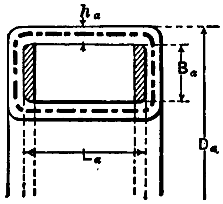


FIG. 18.—LENGTH OF MEAN TURN IN RING ARMATURE.

For *smooth-core drums,* $k = 1.25$ to 1.75; average, $k = \mathbf{1.5}$;
" *toothed drums,* $k = 1.5$ to 3.0; average, $k = \mathbf{2.25}$.

The smaller values apply to large armatures having a comparatively small winding depth (below the average given in Table **14**), whereas the larger values are for small armatures in which the winding depth is comparatively large (above the corresponding average given in Table **14**).

For a spirally wound *ring armature*—that is, one in which the turns are completed spirally by winding the inner surface of the ring—the total length of the armature wire is directly given by the dimensions of the armature core, thus:

$$l_A = N \times \frac{2L_a + 2B_a + h_a\pi}{12}, \qquad\qquad (\mathbf{26})$$

where l_A = total length of armature wire, in feet;
N = number of armature inductors;

and $(2L_a + 2B_a + h_a\pi)$ = length of mean turns, in inches (see Fig. 18), L_a being the length and B_a the radial thickness of the armature core, and h_a the winding depth.

In case of *formed coils*, which are separately completed by means of formers and placed upon the *exterior* surface of the armature, the total length of the winding is found from formula (**24**) or (**25**), in which then the constant k has the following approximate values:

For coils spanning $\frac{1}{4}$ circumference (*4* poles), k = *1.2*
“ “ “ $\frac{1}{6}$ “ (*6* “), “ = *.8*
“ “ “ $\frac{1}{8}$ “ (*8* “), “ = *.6*
“ “ “ $\frac{1}{10}$ “ (*10* “), “ = *.5*
“ “ “ $\frac{1}{12}$ “ (*12* “), “ = *.4*
“ “ “ $\frac{1}{16}$ “ (*16* “), “ = *.3*
“ “ “ $\frac{1}{24}$ “ (*24* “), “ = *.2*

39. Armature Resistance.—The electrical resistance of the armature winding is determined by the total length of wire wound on the armature and by the sectional area of the conductor. If R_a denotes the total resistance of the armature wire, all in one continuous length, and if there are n_p bifurcations in the armature, and, therefore, $2n_p$ electrically parallel armature circuits, then the armature forms the combination of $2n_p$ parallel branches of $\frac{R_a}{2n_p}$ ohms resistance each; their joint resistance, r_a, which is the actual armature resistance, will consequently be:

$$r_a = \frac{1}{2n_p} \times \frac{R_a}{2n_p} = \frac{R_a}{4n_p^2}.$$

The total resistance R_a of the armature conductor is the product of the total length l_A and the resistivity, ρ_f, in ohms per foot of the conductor, hence the armature resistance:

$$r_a = \frac{l_A \times \rho_f}{4n_p^2} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots (27)$$

In case that the armature conductor is subdivided into two or more wires, the resistivity of that wire must be divided by the number of wires used in parallel. The resistivities, ρ_f, of the various sizes of armature wire at 20° C. (68° Fahr.) are given in column *5* of Table **13**. When using these figures, therefore, the armature resistance found by (**27**) is that at ordinary room temperature, or is the *cold* resistance of the armature when the machine is not running. In order to obtain the *warm* armature resistance, add *1* per cent. for every *2½* degrees C. over 20° C., or *1* per cent. for every *4½* degrees Fahr. over 68° F. Thus, if the temperature of the armature, when running at full load, is about *60°* C. (= *140°* F.), which is the usual limit given in dynamo specifications, the value found by (**27**) must be increased by $\frac{60 - 20}{2\frac{1}{2}} = \frac{40}{2.5} = 16$ per cent., or must be multiplied by **1.16**. Figuring in Fahr. degrees, we have $\frac{140 - 68}{4\frac{1}{2}} = \frac{72}{4.5} = 16$ per cent., the same as before.

40. Example of Drum Armature.—*A bipolar drum armature,* **16** *inches in diameter and* **25** *inches in length, contains* **192** *inductors, each consisting of* **3** *No.* **5** *B. & S. wires. What is the armature resistance at* **70°** *C.?*

Solution.—In this case $N = 192$, $L_a = 25$, $D_a = 16$, and $k = 1.5$ (the armature being of medium size); hence, by (**25**):

$$l_a = \frac{192}{12}(25 + 1.5 \times 16) = \frac{192 \times 49}{12} = 784 \text{ feet.}$$

The resistivity of No. *5* B. & S. wire, according to Table **13**, is *.000313* ohm per foot; since *3* such wires are used in parallel, the resistivity of the armature conductor in the present example is .000313 ÷ 3 = .000104 ohm per foot. The number of bifurcations in a bipolar machine is $n_p = 1$. Therefore, the armature resistance at *20°* C., from formula (**27**):

$$r_a = \frac{784 \times .000104}{4} = .0020 \text{ ohm.}$$

At *70°* C., the resistance is $\frac{70 - 20}{2\frac{1}{2}} = 20$ per cent. higher, or

$$r_a' = 1.20 \times .0020 = \mathbf{.0024} \text{ ohm.}$$

41. Example of Ring Armature.—*Find the resistance at* **150°** *F. of a* **12**-*pole ring armature which is wound with* **107** *sections, each of* **6** *turns of* **12** *strands of No.* **7** *B. & S. wire, if its dimensions are as follows: Diameter,* **106** *inches; length,* **26** *inches; radial thickness,* **5½** *inches; winding depth,* **¾** *inch.*

Solution.—The total number of inductors in this armature is 107 × 6 = *642;* hence by formula (**23**):

$$L_A = 642 \times \frac{2 \times 26 + 2 \times 5\frac{1}{2} + \frac{3}{4} \times \pi}{12} = 3{,}500 \text{ feet.}$$

From Table **13**, the resistivity of No. *7* wire is *.000497* ohm per foot; the value of ρ_f, therefore, as there are *12* wires in parallel in this case, is .000497 ÷ 12 = *.0000414*. The number of bifurcations in a multipolar machine being equal to the number of pairs of poles, we have from (**27**):

$$r_a = \frac{3{,}500 \times .0000414}{4 \times 6^2} = .001006 \text{ ohm at } 68° \text{ F.}$$

To find the resistance at 150° F. we must increase this value by $\frac{150 - 68}{4\frac{1}{2}} = 18.2$ per cent.; hence we have:

$$r_a = 1.182 \times .001006 = \mathbf{.00119} \text{ ohm.}$$

42. Check on Armature Calculation with Reference to Heating Limit.—The dimensions and the winding of the armature having been determined, it will be well, before going into the design of the magnet frame, to investigate whether the armature as designed fulfills the requirements as to its heating limit.

For this purpose we must determine the power losses due to the resistance of the winding, to hysteresis of the iron, and to the production of eddy currents in the core. The total loss being found, its ratio to the cooling surface of the armature determines the approximate rise of temperature of the armature.

If the latter is too high, the ratio of power loss to the cooling surface must be correspondingly decreased, either by increasing the cooling surface or by decreasing the power loss, or by a combination of both expedients. The cooling surface is increased by increasing the size of the armature, and at the same time the latter is enabled to accommodate a larger size of conductor, thus reducing its resistance and lowering the power loss in the winding.

An excessive rise of the temperature is usually the result of having assumed too great a winding depth; in re-designing the armature, particular attention should therefore be bestowed upon this point. The winding depth may be decreased either by reducing the number of layers of the armature wire, or by so subdividing the armature conductor that a suitable winding depth can be obtained by a proper rearrangement of the wires.

43. Power Consumed in Armature Winding.

—The power lost in the armature winding of a dynamo or motor is the square of the current in the armature multiplied by the armature resistance, or in symbols:

$$w_a = C^2 \times r_a', \qquad (28)$$

where w_a = power dissipated in armature winding, in watts;

C = total current flowing in armature, in amperes;

r_a' = armature resistance, *warm*, in ohms.

In the case of a series machine, C in formula (28) is identical with the given external current; in shunt and compound-wound machines, however, allowance for the shunt excitation must be made. The amount of current passing through the shunt winding is the terminal E. M. F. of the machine divided by the resistance of the shunt circuit. The latter not having been determined at this stage of the design, the shunt current may be taken approximately from Table **18**:

TABLE 18.

APPROXIMATE SHUNT CURRENT IN SHUNT AND COMPOUND-WOUND DYNAMOS.

Capacity, in Kilowatts.	Shunt Current, in per cent. of Current Output.
.1	15% to 12%
.5	10 " 8
1	8 " 7
2.5	7 " 6
5	6 " 5
10	5 " 4
25	4 " 3
50 to 100	3 " 2.5
100 " 300	2.5 " 2
500 and over.	2 " 1.5

To obtain the current in the armature, the shunt current must be *added* to the desired current output, in case of a *generator;* and *deducted* from the given supply current, in case of a *motor.*

44. Power Lost by Hysteresis.—The hysteresis loss in the armature core is proportional to the frequency of reversal and to the mass of iron contained in the core:

$$w_h = \eta \times f \times M, \qquad (29)$$

where w_h = hysteresis loss, in watts;

η = *hysteresis factor*, that is, the hysteresis loss in 1 cubic inch of iron at a frequency of 1 cycle per second, see Table **19**;

f = frequency, in cycles per second;

and M = mass of iron in armature core, in cubic inches.

The frequency is the number of revolutions per second multiplied by the number of pairs of magnet poles, or

$$f = \frac{n_1}{60} \times n_p. \dots\dots\dots\dots \quad (30)$$

The mass, M, when allowing 10 per cent. of the core length for spaces between the laminæ, is given by the formula:

$$M = (D_a - B_a)\pi \times B_a \times .9L_a, \dots\dots\dots\dots (31)$$

TABLE 19.

HYSTERESIS FACTOR FOR DIFFERENT FLUX DENSITIES.

Density, in Lines per Square Inch. B_a.	Hysteresis Factor. Watts per Cu Inch. η.	Density, in Lines per Square Inch. B_a	Hysteresis Factor. Watts per Cu. Inch. η.	Density, in Lines per Square Inch. B_a.	Hysteresis Factor. Watts per Cu. Inch η.
10000	.0007	60000	.0128	82000	.0211
15000	.0014	61000	.0131	83000	.0215
20000	.0022	62000	.0135	84000	.0219
25000	.0031	63000	.0138	85000	.0223
30000	.0042	64000	.0142	86000	.0227
32500	.0048	65000	.0145	87000	.0232
35000	.0054	66000	.0149	88000	.0236
37500	.0060	67000	.0152	89000	.0240
40000	.0067	68000	.0156	90000	.0245
42500	.0074	69000	.0160	92500	.0253
45000	.0081	70000	.0164	95000	.0261
47500	.0088	71000	.0167	97500	.0275
50000	.0095	72000	.0171	100000	.0289
51000	.0098	73000	.0175	105000	.0312
52000	.0102	74000	.0179	110000	.0337
53000	.0105	75000	.0183	115000	.0362
54000	.0108	76000	.0187	120000	.0387
55000	.0111	77000	.0191	125000	.0414
56000	.0114	78000	.0195	130000	.0442
57000	.0117	79000	.0199	135000	.0470
58000	.0121	80000	.0203	140000	.0498
59000	.0124	81000	.0207	145000	.0527

where M = Mass of iron in armature core, in cubic inches;
D_a = diameter of armature core, in inches; for a toothed armature, D_a is the diameter at the root of the teeth;
B_a = radial thickness of armature core, in inches;
L_a = length of armature core, in inches.

In toothed armatures the hysteresis loss in the teeth, calculated by (**29**), in which the mass M is then that of the teeth, must be added to the hysteresis loss in the core.

The hysteresis factor η depends upon the magnetic density; its numerical value for any density is obtained in ergs per cubic centimetre by multiplying the 1.6th power of this density (expressed in lines per square centimetre) by the ***hysteresis constant*** or ***coefficient of hysteresis*** for the respective material; see Par. **262**, Book **13**. Practical values of η, in watts per cubic inch, for various flux densities in *sheet iron*, are given in Table **19**.

45. Power Lost by Eddy Currents.—The power consumed in setting up induced *eddy currents* in a body of iron subjected to reversing or varying magnetization increases with the square of the frequency and is proportional to the mass of the iron:

$$w_e = \varepsilon \times f^2 \times M, \qquad (32)$$

where w_e = eddy current loss, in watts;
ε = eddy current factor, or eddy current loss in 1 cubic inch of iron at a frequency of 1 cycle per second, see Table **20**;
f = frequency, in cycles per second, see formula (**30**);
M = mass of iron, in cubic inches, see formula (**31**).

The eddy current factor, ε, increases with the square of the flux density and with the square of the thickness of the sheets employed in building up the iron body. Table **20** gives the values of ε in watts per cubic inch at unit frequency for flux densities of from *10,000* to *145,000* lines per square inch, for sheet thicknesses of *.010*, *.020*, and *.040* inch.

TABLE 20.

EDDY CURRENT FACTORS FOR DIFFERENT FLUX DENSITIES AND THICKNESSES OF LAMINATION.

Density. Lines pr. sq. inch.	Eddy Current Factor, ε. Watts per cubic inch. Thickness of Lamination:			Density. Lines pr. sq. inch	Eddy Current Factor, ε. Watts per cubic inch. Thickness of Lamination:		
B_a	.010″	.020″	.040″	B_a	.010″	.020″	.040″
10000	.0000004	.000002	.000007	85000	.000030	.000121	.000483
20000	.000002	.000007	.000027	87500	.000032	.000128	.000513
30000	.000004	.000015	.000060	90000	.000034	.000136	.000542
40000	.000007	.000027	.000107	92500	.000036	.000143	.000573
45000	.000009	.000034	.000136	95000	000038	.000151	.000603
47500	.000010	.000038	.000152	97500	.000040	.000159	.000636
50000	.000011	.000042	.000167	100000	.000042	.000167	000669
52500	.000012	.000046	.000185	102500	.000044	.000176	.000703
55000	.000013	.000051	.000203	105000	.000046	.000184	.000737
57500	.000014	.000056	.000222	107500	000049	.000194	.000774
60000	.000015	.000060	.000241	110000	.000051	.000203	.000810
62500	.000017	.000066	.000262	112500	.000053	.000212	.000848
65000	.000018	.000071	.000282	115000	.000055	.000221	.000885
67500	.000019	.000076	.000305	117500	.000058	.000231	.000925
70000	.000021	.000082	.000328	120000	.000060	.000241	.000964
72500	.000022	.000088	.000352	125000	.000066	.000262	.001046
75000	.000024	.000094	.000376	130000	.000071	.000283	.001130
77500	.000025	.000101	.000402	135000	.000076	.000305	.001218
80000	.000027	.000107	.000428	140000	.000082	.000328	.001311
82500	.000029	.000114	.000456	145000	.000088	.000351	.001405

46. Specific Power Loss in Armature.—Having computed the power losses in the armature, their sum divided into the cooling surface gives the actual specific cooling surface of the armature, which, as stated in Par. **16**, should be between *.5* and *.75* square inch per watt for a drum armature, and between *.75* and *1.0* square inch per watt for a ring armature:

$$s = \frac{S_a}{w_a + w_h + w_e}, \ldots\ldots\ldots\ldots\ldots (33)$$

where s = specific cooling surface of armature;
S_a = cooling surface of armature, formula (**7**) or (**9**), respectively;
w_a = power lost in armature winding, formula (**28**);
w_h = " " " hysteresis, " (**29**);
w_e = " " " eddy currents, " (**32**).

If the value of s found by (**33**) is below *.5* for a drum, or below *.75* for a ring armature, the armature would heat up excessively, and should therefore be redesigned, as indicated in Par. **42**.

47. Temperature Increase of Armature.—Approximate limits of the temperature increase of practical armatures, as actually found for various values of the specific cooling surface s, are given in Table **21**. By means of

TABLE 21.

TEMPERATURE INCREASE OF ARMATURE FOR DIFFERENT SPECIFIC COOLING SURFACES.

Specific Cooling Surface. Sq. inches p. watt.	Temperature Increase.			
	Drum Armature.		Ring Armature.	
	Centigrade.	Fahrenheit.	Centigrade.	Fahrenheit.
.4	50° to 75°	90° to 135°	60° to 100°	108° to 180°
.5	45 " 70	81 " 126	55 " 90	99 " 162
.6	40 " 60	72 " 108	50 " 80	90 " 144
.7	35 " 50	63 " 90	45 " 70	81 " 126
.8	30 " 45	54 " 81	40 " 60	72 " 108
.9	25 " 40	45 " 72	35 " 50	63 " 90
1.0	20 " 35	36 " 63	30 " 45	54 " 81
1.25	15 " 25	27 " 45	25 " 40	45 " 72
1.5	10 " 20	18 " 36	20 " 30	36 " 54
2.0	5 " 15	9 " 27	15 " 25	27 " 45

this table the designer will be able to predict, from the result obtained by formula (**33**), the approximate rise of temperature in the armature.

48. Circumferential Current Density of Armature.

—An excellent check on the heat calculation of the armature, and in many cases the only investigation made as to its heating properties, is the computation of the **circumferential current density,** that is, the total number of amperes carried per inch of the armature circumference. The circumferential current density is found by dividing the total number of amperes all around the armature by the core periphery:

$$c = \frac{N \times \frac{C}{2n_p}}{D_a \times \pi} = \frac{N \times C}{6.283 \times D_a \times n_p} \quad \ldots\ldots\ldots\ldots\ldots (\mathbf{34})$$

c = circumferential current density, in amperes per inch of armature circumference;
N = total number of armature conductors;
C = total current at armature terminals, in amperes;
$2n_p$ = number of parallel circuits in armature winding;
D_a = diameter of armature core, in inches.

Having found c from (**34**), a comparison with Table **22**, compiled from actual machines of various types, gives an idea of the temperature increase that may be expected in the calculated armature when completed. By comparing the average increase derived from Table **22** with the average obtained from Table **21**, a very close approximation to the actual value of the temperature increase of the armature can usually be gained.

49. Example of Smooth-Drum Armature.

—*A bipolar smooth-drum armature to produce* **40** *amperes at a constant E. M. F. of* **125** *volts when running at* **1,800** *revolutions per minute, has been calculated as follows: Diameter,* **5¾** *inches; length,* **9¼** *inches; radial depth of core discs,* **1⅞** *inches; winding,* **336** *conductors,* *No.* **9** *B. & S.; resistance (at 20° C.),* **.105** *ohm. Find the probable temperature increase.*

TABLE 22.

TEMPERATURE INCREASE OF ARMATURE CORRESPONDING TO DIFFERENT CIRCUMFERENTIAL CURRENT DENSITIES.

Circumferential Current Density. Amps. p. inch.	Temperature Increase of Armature.			
	High-Speed Dynamos.		Low-Speed Dynamos.	
	Centigrade	Fahrenheit	Centigrade.	Fahrenheit.
50 to 100	15° to 25°	27° to 45°	10° to 20°	18° to 36°
100 " 200	20 " 35	36 " 63	15 " 25	27 " 45
200 " 300	30 " 50	54 " 90	20 " 35	36 " 63
300 " 400	40 " 60	72 " 108	25 " 40	45 " 72
400 " 500	50 " 70	90 " 126	30 " 45	54 " 81
500 " 600	60 " 80	108 " 144	35 " 50	63 " 90
600 " 700	70 " 90	126 " 162	40 " 60	72 " 108
700 " 800	80 " 100	144 " 180	50 " 70	90 " 126
800 " 1000	....	....	60 " 80	108 " 144

Solution.—The warm resistance of this armature can be approximately taken as 1.16 × .105 = .122 ohm, see Par. **39.** The shunt current of a 5 K. W. dynamo, according to Table **18,** is between 5 and 6 per cent. of the terminal current; the total current, therefore, in this case is about 1.05 × 40 = **42** amperes. Hence, the power absorbed in the winding, by formula (**28**):

$$w_a = 42^2 \times .122 = \mathbf{214} \text{ watts.}$$

The frequency, from (**30**), is:

$$f = \frac{1800}{60} \times 1 = \mathit{30} \text{ cycles per second.}$$

The mass is found by (**31**):

$$M = (5\tfrac{3}{4} - 1\tfrac{7}{8})\pi \times 1\tfrac{7}{8} \times .9 \times 9\tfrac{1}{4} = \mathit{190} \text{ cubic inches.}$$

The flux density, $\mathbf{B}_a$, in the armature, is the flux divided by the armature cross-section. The flux in the present case is:

$$\Phi = \frac{6 \times 10^9 \times 1 \times 125}{336 \times 1800} = \mathit{1,240,000} \text{ lines, see } (\mathbf{21}),$$

and the cross-section of the armature:

$$2B_a \times .9L_a = 1.8 \times 1\tfrac{7}{8} \times 9\tfrac{1}{4} = \mathit{31} \text{ square inches.}$$

Hence we have:

$$\mathbf{B}_a = \frac{1,240.000}{31} = \mathit{40,000} \text{ lines per square inch;}$$

and, the hysteresis factor, from Table **19,** $\eta = .0067$. From (**29**) we therefore obtain the power absorbed by hysteresis:

$$w_h = .0067 \times 30 \times 190 = \mathbf{38} \text{ watts.}$$

The eddy current factor for a flux density of 40,000 lines per square inch, if the sheet iron used is .020 inch thick, is $\varepsilon = .000027$, according to Table **20,** consequently the power absorbed by eddy currents. from (**32**):

$$w_e = .000027 \times 30^2 \times 190 = \mathbf{5} \text{ watts.}$$

The approximate cooling surface of the armature, from (**7**), is:

$$S_a = 5\tfrac{3}{4}\ \pi \times 9\tfrac{1}{4} + (5\tfrac{3}{4})^2 \frac{\pi}{4} = 167 + 26 = \mathit{193} \text{ sq. in.}$$

Dividing S_a by the total power loss in the armature, the specific cooling surface is obtained, see (**33**):

$$s = \frac{193}{214 + 38 + 5} = \mathbf{.75} \text{ square inch per watt.}$$

The average temperature increase corresponding to this value, according to Table **21,** is about **40° C.**

By formula (**34**) the circumferential current density of the given armature is:

$$c = \frac{336 \times 42}{6.283 \times 5\tfrac{3}{4} \times 1} = \mathbf{390} \text{ amperes per inch.}$$

For this value of c, Table **22** gives an average of **50°** C. in the present case of a high-speed machine.

Taking the mean of the two averages found, we obtain $\frac{1}{2}(40 + 50) = \mathbf{45°}$ C. as the approximate average temperature rise of the armature.

The armature here considered is that of a machine in actual use. It has a temperature rise of *42*° C. when running continuously at full load.

50. Example of Toothed Ring Armature.—*It is assumed that the design of a toothed ring armature for a* **4**-*pole* **330** *K. W. compound-wound railway generator for an output of* **600** *amperes at* **550** *volts, when running at a speed of* **400** *revolutions per minute, has resulted in the following data: External diameter of core,* **44½** *inches; internal diameter,* **21½** *inches; length,* **25** *inches; radial depth of solid portion,* **9¾** *inches; number of slots,* **90**; *width of slots, ⅞ inch; depth of slots,* **1¾** *inches; winding,* **4** *copper strips, ½ inch by ¼ inch, per slot; armature resistance, at 20° C.,* **.0087** *ohm. Required to predetermine the approximate rise of the armature temperature.*

Solution.—

Warm resistance: $r_a' = 1.16 \times .0087 = .0101$ ohm;

Total current (Table **18**): $C = 1.02 \times 600 = 612$ amps;

∴ Power absorbed by armature winding, formula (**28**):

$$w_a = 612^2 \times .0101 = \mathbf{3{,}780} \text{ watts.}$$

Frequency, formula (**30**): $f = \frac{400}{60} \times 2 = 13.33$ cycles;

Diameter at roots of teeth: $44\frac{1}{2} - (2 \times 1\frac{3}{4}) = 41$ inches.

Mass of body, formula (**31**):

$$M = (41 - 9\tfrac{3}{4})\,\pi \times 9\tfrac{3}{4} \times .9 \times 25 = 21{,}537 \text{ cu. in.}$$

Mass of teeth, Fig. 19:

$$\left[(44\tfrac{1}{2})^2\frac{\pi}{4} - (41)^2\frac{\pi}{4} - 90 \times 1\tfrac{3}{4} \times \tfrac{7}{8}\right] \times .9 \times 25 = 2{,}400 \text{ cu. in.};$$

Flux per pole, formula (**21**):

$$\Phi = \frac{6 \times 10^8 \times 550}{(90 \times 4) \times 40} = \mathit{22{,}971{,}000} \text{ lines;}$$

Cross-section of body: $1.8 \times 9\frac{3}{4} \times 25 = \mathit{438}$ sq. ins.;
Cross-section at roots of teeth opposite one pole :

$$\frac{41 \times \pi - 90 \times \frac{7}{8}}{4} \times .9 \times 25 = \mathit{277} \text{ sq. ins.;}$$

Flux density in armature body:
$22{,}917{,}000 \div 438 = 52{,}300$ lines per square inch;
Flux density in teeth:
$22{,}917{,}000 \div 277 = \mathit{83{,}000}$ lines per square inch;
Hysteresis factor for body (Table **19**): $\eta = \mathit{.0103;}$
Hysteresis factor for teeth (Table **19**): $\eta = \mathit{.0215;}$

$\therefore$ Power loss by hysteresis:
$w_h = .0103 \times 13.33 \times 21{,}537 + .0215 \times 13.33 \times 2{,}400$
$= 2{,}960 + 690 =$ **3,650** watts.

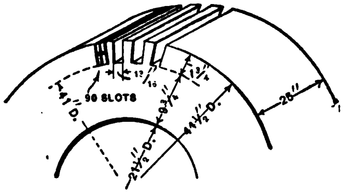


FIG. 19.—DIMENSIONS OF 330 K W. TOOTHED RING ARMATURE.

Supposing the iron used in this armature is *.015* inch thick. Since the eddy current loss is proportional to the square of the thickness, and since .015" = 3/2 × .010", we must multiply the factor found in Table **20** for .010" iron at the given flux density by $(\frac{3}{2})^2$, or by $\frac{9}{4}$. The eddy current factor for 52,300 lines and .010" iron is *.000012;* hence, for .015" iron, $\varepsilon = .000012 \times \frac{9}{4} = \mathit{.000027}$. Similarly for 83,000 lines (density in teeth), $\varepsilon = .000030 \times \frac{9}{4} = \mathit{.000068}$.

∴ Power loss by eddy currents:

$w_e = 000027 \times 13.33^2 \times 21{,}537 + .000068 \times 13.33^2 \times 2{,}400$

$= 104 + 29 =$ **133** watts.

Cooling surface (Fig. 19):

$S_a = (44\frac{1}{2} - 11\frac{1}{2})\pi \times 2(25 + 11\frac{1}{2}) =$ *7560* square inches;

Total energy loss in armature:

$3{,}780 + 3{,}650 + 133 =$ *7,563* watts;

∴ Specific cooling surface, by (**33**):

$s = 7{,}560 \div 7{,}563 =$ *1.0* square inch per watt.

The average rise of temperature corresponding to $s = 1$, from Table **21,** is **37½**° C.

Circumferential current density, by (**34**):

$$c = \frac{(90 \times 4) \times 612}{6.283 \times 44\frac{1}{2} \times 2} = \mathbf{394} \text{ amperes per square inch.}$$

Average temperature increase corresponding to $c = 394$, from Table **22,** for high-speed dynamo, **50**° C.

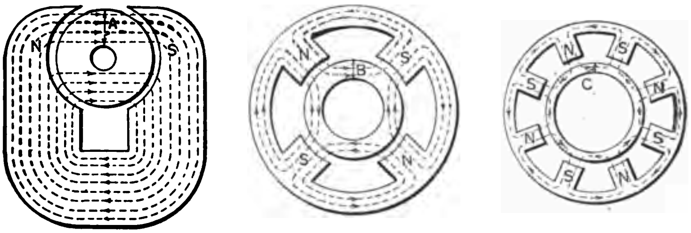
Mean of the two averages: $\frac{1}{2}(37\frac{1}{2} + 50) =$ **44**° C.

The actual rise of the temperature in this armature, which is that of an existing machine, is about *45*° C.

THE DESIGN OF DIRECT-CURRENT DYNAMOS AND MOTORS.

DESIGN OF FIELD MAGNET.

51. General Form of Field Magnet.—With a given size (diameter and length) of armature the value of the total flux, Φ, does not necessarily depend upon the form of the field magnet. This is shown by comparing Figs. 20, 21, and 22, in which armatures of equal size are represented in bipolar, four-pole, and eight-pole fields. Assuming that in all three cases the polepieces cover a like portion of the armature periphery, then the total number of magnetic lines entering and leaving the surface of the armature is the same in the three designs. This is evident when it is considered that by the above assumption the total number of square inches covered by the polepieces in Figs. 21 and 22 is equal to those in Fig. 20, and that each square inch contains the same number of lines at the given flux density. In practice the flux density is usually less in bipolar than in multipolar machines, but



FIGS. 20, 21, AND 22.—ARMATURES OF EQUAL SIZE IN BIPOLAR, FOUR-POLE, AND EIGHT-POLE FIELDS.

this difference is not a necessity and need not be considered in the preliminary determination.

It is generally known whether the machine is to have two poles or more, but in any case it is an advantage for the designer to be free to alter the form of the field magnet without being obliged to change the general dimensions of the armature, although the relative diameter would ordinarily be made greater for a multipolar machine. The last-named fact, however, need not increase the surface of the armature required for carrying the conductors and getting rid of the heat generated in them.

This brings us to the consideration of the comparative advantages of bipolar and multipolar field magnets, which is a much-discussed question. Prior to 1890, the bipolar construction was generally employed for all direct-current machinery, but since that time the multipolar form has been adopted by nearly all manufacturers in this country and in Europe, for sizes down to about *5* or *10* K. W., and even below this for low-speed machines. In England, however, it is still common practice to build bipolar generators and motors as large as *100* or *200* K. W.

52. Advantages and Disadvantages of Multipolar Machines.—The *advantages* of multipolar dynamos are the following:

(1) Saving in weight of material for both armature and field magnet;
(2) More compact and symmetrical form;
(3) Better ventilation of armature and field magnets;
(4) For armatures of the same diameter, the individual parts of the field frame are much smaller and more easily handled in the multipolar than in the bipolar type.

The *disadvantages* of multipolar machines are:

(1) Greater complication, owing to the increased number of parts and connections;
(2) Strong magnetic side pull on armature, even when only slightly nearer one polepiece than another; much greater than in bipolar field;

(3) With multiple circuit armature windings (Figs. 14 and 15), the flux must be the same for each pole, otherwise the E. M. F. of the circuits will be unequal, producing wasteful currents in them, which, in turn, cause excessive sparking and heating. This difficulty is not present in two-circuit windings (Fig. 16), using only two sets of brushes.

The saving in material is clearly shown by comparing Figs. 20 and 21. In the former, it will be seen that the armature must carry ½ the total flux between its shaft and periphery, while in Fig. 21 the armature cross-section is only required to carry ¼ the total flux, hence the radial depth *B* of the armature core in Fig. 21 need be only one-half as great as *A* in Fig. 20. This allows the core of the four-pole machine to be hollowed out as shown in Fig. 21, thus reducing its weight. It will be observed that the bulk of the field magnet is also less for the multipolar than for the bipolar construction.

The difference is still more marked when we compare the eight-pole machine in Fig. 22 with the bipolar type in Fig. 20. In Fig. 22 the radial thickness of the field ring is only ½ as much as in Fig. 21, and ⅛ as great as the thickness of the yoke in Fig. 20, and the armature may be hollowed out to a radial thickness, *C*, of only ¼ that of the bipolar armature, *A*, as shown, the total flux being the same for all three designs. The external diameters of the armatures being the same, it follows that an equal number of similar inductors can be carried in each case. In short, the capacity of the multipolar machines in Figs. 21 and 22, considered either as generators or motors, is as great as that of the bipolar form in Fig. 20, although the volume of material is decidedly less for the multipolar types.

53. Proper Number of Poles for Multipolar Field Magnets.—In the case of a machine of considerable size, for which a multipolar field would almost surely be adopted, the next step is to decide upon how many poles it is best to employ. This is a question partly of selecting a size and number of field cores, coils, etc., convenient for making and handling, but it is chiefly a matter of the number of *magnetic cycles* per second occurring in the armature core. If we consider any particular cubic inch of the iron forming this core, it is evident that its magnetism is reversed once for each pole that it passes. A complete cycle of magnetic changes takes place in passing a north and a south pole, hence the number of cycles per second is the number of *pairs* of poles passed in one second, that is,

$$f = \frac{n_1 \times n_P}{60} \dots\dots\dots\dots\dots\dots (35)$$

In this expression, f is the number of cycles per second, corresponding to the **frequency** of an alternating current; n_1 is the speed of the armature, in revolutions per minute; and n_P is the number of *pairs* of field magnet poles.

Direct-current machinery is designed, generally, so that f is between *10* and *35* cycles per second. This limits the number of poles, the object being to reduce the core losses, that is, the losses due to *hysteresis* and *eddy currents* in the armature, the former, as we have seen in Par. **44**, being proportional to f, whereas the latter increase with the square of f, Par. **45**. The lower frequency of about *10* or *15* cycles applies to low-speed machines for direct connection to engines, etc., and the higher frequency of *30* or *35* is adopted in high speed, belt-connected generators and motors.

By transformation of (**35**), it follows that the maximum speed of a *four-pole* machine (*2 pairs* of poles) should be

$$n_1 = \frac{60 \times f}{n_P} = \frac{60 \times 35}{2} = \mathbf{1050} \text{ revs. per min.}$$

In some instances, four-pole machines are run at higher speeds than this; for example, *1200* revs. per min., which gives *40* cycles. But this is rather too high a frequency, and should not be adopted except for special reasons.

If the values $n_p = 1, 2, 3, 4$, etc., and $f = 10, 15, 25$, and 35 be inserted in the above formula for n_1, the following table of dynamo speeds for various numbers of poles is obtained. From this table the proper number of poles for low, medium, and high speed machines of given speeds can be readily taken.

TABLE 23.

NUMBER OF MAGNET POLES FOR VARIOUS SPEEDS.

Number of Poles.	Limits of Speeds.		
	Low Speed Machines. $f = 10$ to 15.	Medium-Speed Machines. $f = 15$ to 25.	High Speed Machines $f = 25$ to 35.
2	600 to 900	900 to 1500	1500 to 2100
4	300 " 450	450 " 750	750 " 1050
6	200 " 300	300 " 500	500 " 700
8	150 " 225	225 " 375	375 " 525
10	120 " 180	180 " 300	300 " 420
12	100 " 150	150 " 250	250 " 350
14	85 " 130	130 " 215	215 " 300
16	75 " 115	115 " 190	190 " 260
18	70 " 100	100 " 170	170 " 230
20	60 " 90	90 " 150	150 " 210
24	50 " 75	75 " 125	125 " 175

Generally speaking, the *bipolar type* is used for high speeds, such as *1500* revs. per min. or more. A further reason for selecting the bipolar type for very high speeds is the fact that machines running at 1,5 0 revolutions, or more, are usually quite small. For speeds between *400* and *900* revs. per min. the *four-pole* construction is especially suitable, giving frequencies from *13⅓* to *30* cycles. This includes nearly all belted dynamos and motors, from the large sizes of *200* K. W., or more, down to about *10* K. W., below which the bipolar form is generally used for the reasons given. Between *200* and *400* revs. per min. *6 poles* are commonly adopted, the corresponding frequencies being from *10* to *20* cycles. This range of speed comprises practically all generators directly connected to high-speed engines, from the largest to the smallest, excepting combinations with very high speed engines of *600* revs. per min., or more, for which *4* poles would be preferable. When a dynamo is directly driven by a steam turbine, at an extremely high speed without reducing gear, the field should be of the bipolar type. For speeds below *200* revs. per min. the number of poles is generally increased to *8* or more. This applies to most generators directly connected to low-speed engines.

In some cases motors of various sizes, even down to *1* or *2* H. P., are required to run at low speeds in order to be connected directly to the machines which they drive. For this purpose *6 poles* are suitable for speeds from *200* to *400* revs. per min., and *8 or more poles* if the speed is below *200* revs. per min. Electric railway motors are nearly always constructed with *4* poles, the speed being very variable, but having a maximum value in most cases of about *800* revs. per min. This gives a rather high frequency of *26⅔* cycles, but, as the maximum speed is rarely maintained for more than a few minutes at a time, the heating due to hysteresis and eddy currents in the armature core does not rise above the limit allowed. The average speed corresponds to a moderate frequency of *15* to *20* cycles.

54. Sectional Area of Magnet Frame.—The proper number of poles having been decided upon, the next step is to find the approximate size of the field magnet required in a given case.

The cross section of the field magnet is determined by the total flux which it has to carry, sufficient area being allowed to avoid excessive flux density in the iron. The probable flux in the armature being given by (**21**), it is necessary to make the cross-section of the field cores, and other portions of the field magnet, large enough to carry this useful flux *plus the leakage lines* which do not pass through the armature.

The number of leakage lines is usually from *10* to *50* per cent. of the useful flux for *bipolar toothed-armature* machines. With *bipolar smooth-core* armatures the leakage is considerably greater, ordinarily amounting to from *25* to *100* per cent., according to the size and type of the machine. Hence, the total flux of a bipolar machine is from *1.10* to *2.00* times the useful flux, this multiplier being called the **leakage factor** (see Par. **55**). For *multipolar machines* the general form that has been adopted almost universally is the *ring type*, represented in Figs. 21 and 22; with this form of field magnet the leakage factor ranges from *1.08* to *1.20* in case of a *toothed* armature, and from *1.15* to *1.50* in case of a *smooth* armature, according to the size (see Table **24**).

Denoting the leakage factor by λ, it follows from the preceding that the cross-section of the field magnet is:

$$S_m = \frac{\lambda \times \Phi}{\mathbf{B}_m} = \frac{6 \times 10^9 \times n_p \times E \times \lambda}{N \times n_1 \times \mathbf{B}_m} \text{ sq. ins.}, \ldots. (\mathbf{36})$$

where all symbols have the same meaning as in (**21**), and $\mathbf{B}_m$ is the flux density in the field magnet. The latter should be taken between *80,000* and *100,000* lines per square inch for *wrought iron* and *cast steel,* and between *40,000* and *50,000* lines per square inch for *cast iron.*

In case of *bipolar* machines, S_m is the cross-section of one core; but for multipolar machines, since Φ is the sum of the lines which enter the armature from all the north poles, S_m is the total cross-section of all the north poles, and must therefore be divided by the number of pairs of poles, n_P, in order to give the area of one core.

The *yoke,* or other part connecting the cores, should have a cross-section of $\frac{S_m}{n_P}$ square inches, if it carries all the lines of one south pole to one of the north poles, as in Figs. 20 and 23; or it should have a sectional area of $\frac{S_m}{2n_p}$ square inches, if one-half the lines of each south pole are carried by it to the next north pole on one side, and the other half to the next north pole on the other side, as is the case with the types shown in Figs. 21, 22, and 24.

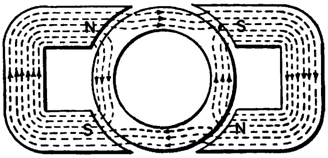


FIG. 23.—FOUR-POLE TYPE, IN WHICH THE YOKE CARRIES ALL THE LINES FROM ONE POLE.

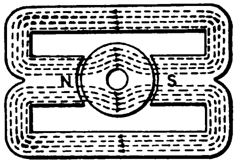


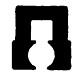
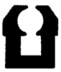
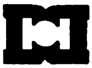
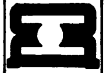
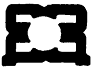
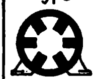
FIG. 24.—BIPOLAR TYPE, IN WHICH THE YOKE CARRIES HALF THE LINES FROM ONE POLE.

55. Factor of Magnetic Leakage.—In Table **24** the usual values of the leakage factor for the types of machines most commonly employed for direct-current dynamos are compiled. The *higher* values for each size refer to the most unfavorable conditions as regards magnetic leakage. namely, to a *smooth-core* armature, to a massive magnet frame with *cast iron polepieces,* and to *high speed.* The *lower* values in each case are for the most favorable magnetic conditions brought about by the employment of a *toothed armature,* a *wrought iron* or *cast steel* field frame, and *low speed.* With *toothed* armatures, the length of the air gap is much less than for smooth-core armatures, hence the gap reluctance is smaller than for a corresponding machine having a smooth armature, and therefore the leakage is proportionately diminished. The use of *wrought iron* or *cast steel* for the field frame has the effect of materially reducing the areas of the leakage paths without much affecting their lengths; the leakage of a wrought iron or cast steel machine is consequently less than that of a cast iron machine, other conditions being the same. In case the machine is designed for *low speed,* its armature will be proportionately larger, and its leakage, therefore, is reduced to that for a correspondingly larger output. In machines of small capacity, the employment of a *ring* instead of a *drum* armature likewise increases the size of the armature and reduces the leakage.

The fact that the leakage factor decreases with the size of the machine is due to the difficulty, or rather impossibility, of advantageously dimensioning the magnetic circuit in small machines. In these the length of the air gaps is comparatively much larger, and the distance of the leakage surfaces much smaller, than in large dynamos; the reluctance of the air gaps, therefore, is relatively much larger, while the reluctances of the leakage paths are considerably smaller, comparatively, than in large machines. Since each of these causes will individually effect a greater leakage, it is evident that their combined result will produce a high value of the leakage factor for a small dynamo.

TABLE 24.

LEAKAGE FACTORS FOR VARIOUS TYPES AND SIZES OF DYNAMOS.

Capacity of Dynamo, in Kilowatts.	Ordinary Horseshoe Type. 	Inverted Horseshoe Type. 	Double Magnet · Type. 	Bipolar Iron Clad Type. 	Fourpolar Iron Clad Type. 	Multipolar Ring Type. 
.1	1.50 to 2.00	1.40 to 1.75	—	1.25 to 1.50	—	—
.25	1.45 · 1.80	1.35 · 1.60	1.45 to 2.00	1.22 · 1.40	—	—
.5	1.40 · 1.70	1.30 · 1.50	1.40 · 1.90	1.20 · 1.35	—	—
1	1.35 · 1.65	1.25 · 1.45	1.35 · 1.80	1.18 · 1.30	—	—
2.5	1.30 · 1.60	1.20 · 1.40	1.30 · 1.70	1.16 · 1.28	1.35 to 1.75	1.20 to 1.50
5	1.25 · 1.55	1.18 · 1.35	1.25 · 1.60	1.14 · 1.25	1.32 · 1.65	1.18 · 1.40
10	1.22 · 1.50	1.16 · 1.30	1.20 · 1.55	1.12 · 1.22	1.30 · 1.60	1.16 · 1.35
25	1.20 · 1.45	1.14 · 1.25	1.18 · 1.50	1.10 · 1.20	1.28 · 1.55	1.15 · 1.32
50	1.18 · 1.40	1.12 · 1.22	1.16 · 1.45	1.09 · 1.18	1.26 · 1.50	1.14 · 1.30
100	1.16 · 1.35	1.10 · 1.20	1.15 · 1.40	1.08 · 1.15	1.24 · 1.45	1.13 · 1.28
200	1.14 · 1.30	—	—	—	1.22 · 1.40	1.12 · 1.25
300	1.12 · 1.25	—	—	—	1.20 · 1.35	1.11 · 1.22
500	—	—	—	—	—	1.10 · 1.20
1000	—	—	—	—	—	1.09 · 1.18
2000	—	—	—	—	—	1.08 · 1.15

56. Length of Magnet Cores.—The length of the magnet cores must be chosen so as to provide sufficient space for the field winding, without, on the other hand, making the length of the magnetic path excessive; or, since the latter consideration usually predominates over the former, the cores should be made as short as possible without increasing the thickness of the winding to an undue amount.

In *bipolar* machines with *toothed* armatures the length of each field core is usually about *1* to *1*½ times the core diameter for *small sizes*, in which the diameter of the magnets is from *2* to *5* inches. For *larger sizes*, up to *18* or *20* inches diameter, the length of the magnet cores is ordinarily from ¾ to *1*¼ times the core diameter; and for diameters above *20* inches, the length is from *10* to *33* per cent. less than the diameter. In the case of a bipolar *smooth-core* armature, the length of the field magnet is about *50* per cent. greater than for a corresponding bipolar *toothed* armature, to give more space for the additional winding required by the larger air gap.

In *multipolar smooth-armature* machines, the usual practice is to make the length of the magnet cores from ½ to *1*¼ times their diameter; for *large* machines the length is chosen between ½ and ¾ of the diameter; for ***medium-sized*** machines between ¾ and *1*; and for *small* machines between *1* and *1*¼ times the diameter. For *toothed-armature* machines the length of the cores is made from ⅔ to ¾ that of a corresponding smooth-armature dynamo.

57. Length of Air Gap.—The air gap is made small with toothed armatures, being determined by the following conditions:

1. Sufficient mechanical clearance for free rotation;
2. Avoidance of eddy currents in the pole faces, explained in connection with Figs. 2 and 3, page 8;
3. Reduction of side pull on armature, especially in multipolar fields (see Par. **52**);
4. Sufficient distance between armature core and pole surface to overcome armature reaction.

63).

As a result of the above considerations, the length of the air gap with toothed armatures is made from $\frac{1}{16}$ inch in *small bipolar* machines to $\frac{1}{4}$ or $\frac{1}{2}$ inch in *large multipolar* ones.

For *smooth-core* armatures the air gap is necessarily greater than for a corresponding toothed armature, as it includes the height of the winding as well as a proper mechanical clearance, which ranges from $\frac{3}{32}$ inch in *small* machines to $\frac{5}{8}$ inch in *large* ones.

TABLE 25.

RADIAL CLEARANCE BETWEEN ARMATURE AND POLEPIECES.

Diameter of Armature, in inches.	Smooth-Core Armature.		Toothed or Perforated Armature.
	Drum.	Ring.	
2	$\frac{3}{32}''$	..	$\frac{1}{16}$
4	$\frac{1}{8}$	$\frac{3}{32}$	$\frac{5}{64}$
8	$\frac{5}{32}$	$\frac{1}{8}$	$\frac{3}{32}$
12	$\frac{3}{16}$	$\frac{5}{32}$	$\frac{1}{8}$
18	$\frac{7}{32}$	$\frac{3}{16}$	$\frac{5}{32}$
24	$\frac{1}{4}$	$\frac{7}{32}$	$\frac{3}{16}$
30	$\frac{9}{32}$	$\frac{1}{4}$	$\frac{7}{32}$
40	..	$\frac{9}{32}$	$\frac{1}{4}$
50	..	$\frac{5}{16}$	$\frac{9}{32}$
75	..	$\frac{3}{8}$	$\frac{5}{16}$
100	..	$\frac{7}{16}$	$\frac{11}{32}$
125	..	$\frac{1}{2}$	$\frac{3}{8}$
150	..	$\frac{9}{16}$	$\frac{7}{16}$
200	..	$\frac{5}{8}$	$\frac{1}{2}$

Table **25** gives the clearances usually allowed for various types and sizes of armatures. For toothed and perforated armatures the figures given are at the same time the lengths of the air gaps, but for smooth armatures the clearance must be added to the height of the winding space given in Table **14**, in order to obtain the length of the air gap.

58. Example.—*Determine the approximate size and form of field magnet required for an armature,* **12** *inches in diameter and* **10½** *inches long, to run at* **1,200** *revolutions per minute.*

Solution.—With this size and speed, either the bipolar or the four-pole construction may be adopted. Let us consider both cases, taking the bipolar type first.

We will assume that it was found in calculating this armature that the flux required to cause the desired output is $\Phi = 5{,}000{,}000$ lines. This, as can be found by means of formula (**22**), would make the field density about

$$\mathbf{B}_g = \frac{5{,}000{,}000}{1.3 \times 12 \times 10\frac{1}{2}} = 30{,}500 \text{ lines per square inch,}$$

which is a good value for an armature of the given size.

The usual leakage factor for this size of *bipolar* smooth-armature machine is about $\lambda = 1.40$; consequently, the total flux in the field magnet will be

$$\Phi' = 1.4 \times 5{,}000{,}000 = 7{,}000{,}000 \text{ lines.}$$

The cores in the present case will preferably be made of *wrought iron,* for which the average practical flux density is $\mathbf{B}_m = 90{,}000$; hence, the required cross-section of the field magnet:

$$S_m = \frac{\Phi}{\mathbf{B}_m} = \frac{7{,}000{,}000}{90{,}000} = 77.8 \text{ square inches.}$$

If circular cores are used, their diameter should consequently be:

$$D_m = \sqrt{S_m \times \frac{4}{\pi}} = \sqrt{77.8 \times 1.273} = \mathbf{10} \text{ inches.}$$

The approximate length of the magnets, in the case of an armature with a *toothed* core, according to Par. **56**, is between ¾ and 1¼ times the diameter, if the latter is between 5 and 20 inches. In the present example we will take a multiplier somewhat smaller than the average of the figures given above, say .9, and we have:

$$L_m = 10 \times .9 = \mathbf{9} \text{ inches.}$$

In case of a *smooth* armature, this length should be increased by 50 per cent., for the reason stated in Par. **56**; consequently for the smooth-armature design:

$$L_m = 9 \times 1.5 = \mathbf{13\tfrac{1}{2}} \text{ inches.}$$

59. Bipolar Design.—To lay off the complete magnetic circuit, draw the pole faces AB and CD in Fig. 25, making each an arc of about 135°, corresponding to a polar embrace of 75 per cent. The distance at which these arcs are placed from the 12-inch circle representing the armature depends upon whether the latter has a *toothed* or a *smooth* core. In the former case, the air gap EF should

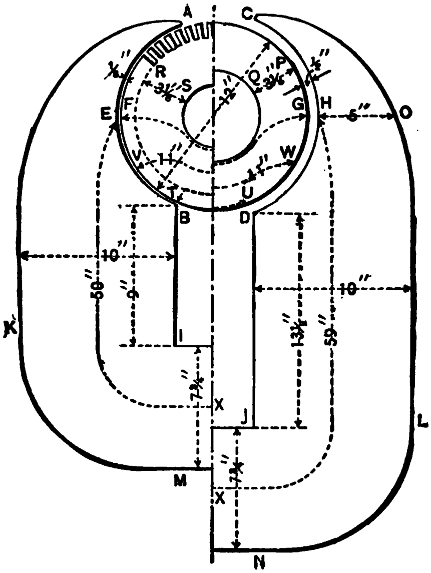


FIG. 25.—MAGNETIC CIRCUIT OF BIPOLAR MACHINE.

be made about ⅛ inch, whereas in the latter case *GH* should be either about ½ inch for a *ring* armature, or about ¾ inch for a *drum* (compare with Tables **14** and **25**).

The lines *BI* and *DJ* are then drawn vertically downward from the points *B* and *D*, a distance equal to the length of the cores, which, since wrought iron polepieces are used, is 9 inches or 13½ inches, according to whether the armature has a toothed or a smooth core, respectively. The diameters *IK* and *JL* are made equal to D_m, which has been found to be 10 inches. In Fig. 25 the toothed-core design is shown at the left side of the center line and the smooth-core design at the right side, so that a comparison can be made at a glance.

The *yoke* of a bipolar machine is usually made of rectangular cross-section having a breadth equal to the diameter of the cores. Its height *IM* or *JN* should therefore in this case be $\frac{77.8}{10} = 7\frac{3}{4}$ inches, provided the same material is employed as for the cores. The cross-section of the yoke is thus made equal to that of the cores, and is kept practically uniform throughout; whereas the polepieces may be tapered, as shown, so that the middle section at *HO* is about ⅔ as large as the core-section, or about

$$\frac{\frac{2}{3} \times 77.8}{10\frac{1}{2}} = \mathbf{5} \text{ inches}$$

thick, the divisor 10½ being the length of the polepieces, which is equal to that of the armature. If the distribution of the lines in the air gaps were uniform, only ½ the total flux would pass through the section *HO*; but when the field is distorted by armature reaction, the flux in the upper half of one of the polepieces may increase to about ⅔ of the total amount.

The *radial depth* of the armature core required to carry the flux Φ is:

$$B_a = \frac{5{,}000{,}000}{2 \times 80{,}000 \times 10\frac{1}{2} \times .95} = 3\frac{1}{8} \text{ inches,}$$

when a flux density of 80,000 lines per square inch of armature cross-section is taken, and when 5 per cent. of the length is allowed for insulation between the armature laminæ. With a *smooth* core this dimension is laid off at *PQ*, and in a *toothed* armature at *RS*. This fixes the internal diameter at

$$12 - (2 \times 3\tfrac{1}{8}) = 12 - 6\tfrac{1}{4} = 5\tfrac{3}{4} \text{ inches,}$$

in the former, and

5¾ inches *minus twice the depth of the teeth*

in the latter case.

It will thus be noted that the effect of putting slots in the armature core, or of varying their depth, is to correspondingly change the internal diameter of the armature. With a *drum* winding this makes no material difference in the design, but with a *ring* winding it is essential to provide sufficient space for the winding to pass through the interior, and also to leave room for the shaft and spider which carry the armature. If the space left after deducting B_a and twice the depth of the slots from the external diameter is found too small for the above purposes, an increase in the internal diameter is necessary which would raise the density of the lines in the armature if the design were left unaltered. To avoid an excessive flux density from this cause, the external diameter of the armature must be correspondingly enlarged, with the consequence of increasing the distance *BD* between the field cores, and of lowering the flux density in the air gap.

60. Four-Pole Design.—If the armature given in Par. **58** is to run in a four-pole field, the armature flux would be the same as before, if the flux density in the air gaps and the polar embrace were the same. In multipolar machines the former is usually somewhat greater, and the latter a little less, than in bipolar machines, hence we will assume that the armature flux is 5,000,000 lines, as in

Par. **58.** The leakage factor, however, is smaller for a multipolar dynamo than for a bipolar machine of equal output; see Pars. **54** and **55.** For a four-pole machine of the size under consideration the average value of λ is about 1.25 instead of 1.40, which it was in the bipolar design. The field flux required for the four-pole frame will therefore be about

$$\Phi' = 1.25 \times 5{,}000{,}000 = \mathbf{6{,}250{,}000} \text{ lines.}$$

Each field core carries one-half of the total flux, because all the useful lines enter the armature from the two pole-pieces of north polarity, and pass to the two south-poles; hence each core must carry 3,125,000 lines. If composed of wrought iron or cast steel, a flux density of 90,000 lines per square inch may be allowed, requiring a sectional area of

$$S_m = \frac{3{,}125{,}000}{90{,}000} = \mathbf{34.7} \text{ square inches.}$$

The corresponding diameter is:

$$D_m = \sqrt{34.7 \times 1.273} = \mathbf{6\tfrac{5}{8}} \text{ inches.}$$

The *length* of the magnets in case of a *smooth*-armature machine, according to Par. **56,** is approximately:

$$L_m = 6\tfrac{5}{8} \times .85 = \mathbf{5\tfrac{5}{8}} \text{ inches,}$$

and in case of a *toothed*-armature machine:

$$L_m = 5\tfrac{5}{8} \times .7 = \mathbf{4} \text{ inches.}$$

In Fig. 26, the field cores for the toothed armature are drawn to scale at *BI,* at the left side of the center line, and for the smooth armature at *DJ,* at the right side, as in Fig. 25.

The *yoke* in the four-pole design carries but half the lines of each magnet, hence its cross-section need only be one-half the area of one magnet core, or 17.4 square inches. Making the frame **8** inches wide, which gives a flange, or overlap, of $\frac{11}{16}$ inch on either side of the cores in the direction of the shaft, the radial thickness *IM* or *JN* of the yoke will be 17.4 ÷ 8 = 2.2, which we will raise to **$2\frac{1}{2}$** inches to allow for rounding the corners of the yoke-section.

With the same armature flux, the *radial depth* of the armature core is one half as great in Fig. 26 as it is in Fig. 25, since in the four-pole design the armature flux is split up into four circuits, while in the bipolar frame there are only two flux paths through the armature (see Par. **52**). Therefore *PQ*, for a smooth core, and *RS*, for a toothed armature, is made $3\frac{1}{8} \div 2 = \mathbf{1\frac{9}{16}}$ inches, which determines the internal diameter. The air gap is left the same as before, being $\frac{1}{8}$ inch for a *toothed* armature and $\frac{1}{4}$ inch for a *smooth ring* core.

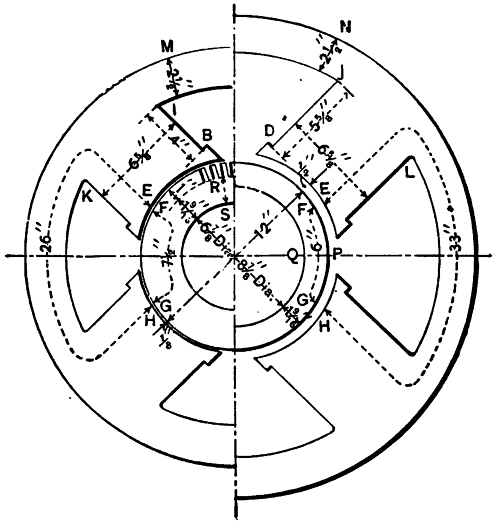


FIG. 26.—MAGNETIC CIRCUIT OF FOUR-POLE MACHINE.

61. Form of Magnet Cores.—In the preceding paragraphs it has been assumed that the field cores were simple cylinders having a straight axis and a circular cross-section. This is ordinarily and preferably the case.

Any departure from a circular cross-section is objectionable for the following reasons:

1. The circle has the least circumference for a given area, even the perimeter of an equivalent square being about 12 per cent. longer; and a rectangle with one side three times the length of the other, has a perimeter nearly 30 per cent. greater than that of a circle of equal area.
2. It is much easier to make a cylinder, since the pattern and core itself can be turned in a lathe.
3. Cylindrical spools for the coils are more easily made than elliptical or rectangular ones.
4. The operation of winding is much more difficult with a rectangular or elliptical core, since the strain on the wire is very unsteady.
5. A rectangular, or even an elliptical, core is much more likely to cause a short-circuit between the turns of wire, since they are forced together at certain points and are liable to cut through the insulation.

Similar arguments apply to a core having a curved axis, that is, those having ring or bow-shaped field-magnet cores. These latter are far more difficult to wind, and possess little or no compensating advantage. The shortness of magnetic circuit which is claimed for them is very doubtful, for the reason that the actual length of core required for equal average depth of winding is greater than if it were straight, since the winding on the inner side of the curve is higher than on the outer side. It often happens that, in the design of dynamos, it is apparently desirable to adopt a core which is not circular in section, or has a curved axis; but it is better to change the entire design in order to avoid these forms, except, perhaps, for a special machine to fit in a certain limited space.

In the case of multipolar magnets of the ring type shown in Figs. 21 and 22, the inner ends of the cores form the pole faces; and since it is desirable for the latter to be rectangular rather than circular, in order to have as much surface as possible, it is a common practice to make the cores rectangular also. But when the pole faces are extended by casting or attaching polepieces to the cores, as in Fig. 26, the latter should have a circular section.

CALCULATION OF MAGNETIZING FORCE.

62. Total Magnetizing Force.—The number of ampere-turns required to produce the necessary flux through the magnetic circuit is the sum of the ampere-turns required to overcome the reluctances of the various parts of the circuit and of the ampere-turns needed to counteract the effect of the armature reaction on the magnetic field. The formula for the total magnetizing force, therefore, is:

$$AT = at_g + at_a + at_m + at_r \ldots\ldots\ldots\ldots (\mathbf{37})$$

in which AT = total number of ampere-turns required;

at_g = ampere-turns necessary to overcome the reluctance of the air gaps;

at_a = ampere-turns to overcome reluctance of armature core;

at_m = ampere-turns to overcome reluctance of magnet frame;

at_r = ampere-turns necessary to compensate for armature reaction (Book **15**, Pars. **56** to **65**).

63. Magnetizing Force Required for any Part of a Circuit.—Each of the three terms at_g, at_a and at_m in the above formula (**37**) can be obtained from the law of the magnetic circuit stated in Par. **35**, Book **15**:

$$Flux = \frac{Magnetomotive\ Force}{Reluctance},$$

which can also be written in the form:

$$Magnetomotive\ Force = Flux \times Reluctance \ldots (\mathbf{38})$$

According to Par. **32**, Book **15**, the reciprocal of *reluctance* is called *permeance*, hence

$$\textit{Magnetomotive Force} = \frac{\textit{Flux}}{\textit{Permeance}}.$$

But the permeance, that is, the magnetic conductance, of a path may be expressed by the permeability of the material and the dimensions of the magnetic path, just as the electric conductance of a body is its conductivity times its area, divided by its length; consequently we have:

$$\textit{Permeance} = \textit{Permeability} \times \frac{\textit{Area}}{\textit{Length}}.$$

Inserting this expression of the permeance into (**38**), we obtain

$$\textit{Magnetomotive Force} = \frac{\textit{Flux} \times \textit{Length}}{\textit{Permeability} \times \textit{Area}},$$

and since the quotient of flux by area is the magnetic flux density **B**, we have

$$\textit{Magnetomotive Force} = \frac{\textit{Density}}{\textit{Permeability}} \times \textit{Length},$$

or

$$\text{M. M. F.} = \frac{\mathbf{B}}{\mu} \times L. \ldots\ldots\ldots\ldots\ldots (\mathbf{39})$$

From (**39**) the magnetomotive force is obtained in *gilberts*, if the density **B** is expressed in lines per square centimetre and the length L, in centimetres; hence, according to Par. **34**, Book **15**:

$$\begin{aligned} \textit{Ampere-turns} &= .796 \times \textit{gilberts} \\ &= .796 \times \frac{\textit{Density}}{\textit{Permeability}} \times \textit{Length}, \end{aligned}$$

or in symbols, practically:

$$at = .8 \times \frac{\mathbf{B}}{\mu} \times L \ldots\ldots\ldots\ldots (\mathbf{40})$$

If the length of the path is given in inches, and the flux density in lines per square inch, we have:

$$\textit{Length in cm.} = 2.54 \times \textit{Length in inches},$$
$$\text{or } L = 2.54 \times L',$$
$$\textit{Lines per square cm.} = \frac{\textit{Lines per square inch}}{6.45},$$
$$\text{or } \mathbf{B} = \frac{\mathbf{B}'}{6.45},$$

in which the inch mark (″) is used as an index to designate the quantities expressed in English measure.

Substituting the above values, formula (**40**) becomes:

$$at = .8 \times \frac{\mathbf{B}''}{6.45\mu} \times 2.54\, L' = .313 \times \frac{\mathbf{B}''}{\mu} \times L'' \ldots (\mathbf{41})$$

The permeability of air being practically 1, the ampere-turns required to overcome the reluctance of the air gap are:

$$at_g = .313 \times \mathbf{B}_g'' \times l_g'', \ldots\ldots\ldots\ldots\ldots (\mathbf{42})$$

in which $\mathbf{B}_g''$ is the flux density per square inch of gap area, and l_g'' is the length in inches of the magnetic paths in both air gaps.

Since $\frac{\mathbf{B}}{\mu}$ in (**39**) is the magnetizing force, **H**, in gilberts per centimetre, it follows that $.313 \times \frac{B''}{\mu}$ in (**41**) is the expression for the magnetizing force, in ampere-turns, required per inch length of the circuit in order to cause a flux density of **B**″ lines per square inch. Designating this *specific magnetizing force* in English units by **H**″, we have:

$$at = \mathbf{H}'' \times L'' \ldots\ldots\ldots\ldots\ldots\ldots (\mathbf{43})$$

In practice, *magnetization curves* are used in which the values of the specific magnetizing force **H**″, corresponding to various densities **B**″, are plotted for the different kinds of iron employed, so that the calculation of the ampere-turns for any part of a magnet circuit resolves itself into the very simple operation of finding from the curve the specific magnetizing force **H**″ for the particu-

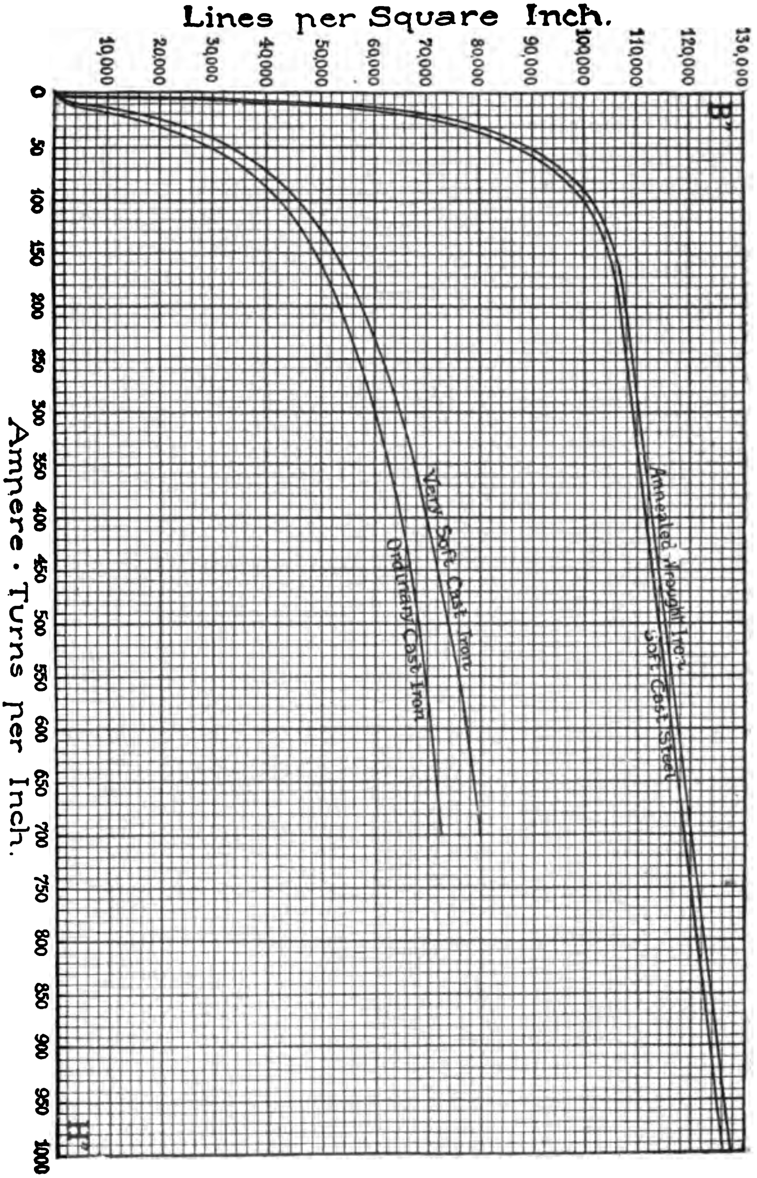


FIG. 27.—MAGNETIZATION CURVES.

lar kind of iron used and for the flux density employed in that part of the circuit, and in multiplying the value so found by the mean length of the magnetic path in the

TABLE 26.

SPECIFIC MAGNETIZING FORCES FOR VARIOUS DENSITIES IN DIFFERENT MAGNETIC MATERIALS.

Flux Density B″ Lines per sq. in.	Ampere-Turns per Inch Length of Circuit, H″.			
	Annealed Wrought Iron.	Soft Cast Steel.	Very Soft Cast Iron.	Ordinary Cast Iron.
5,000	1.7	2.8	10	13
10,000	2.2	3.7	14	19
15,000	2.7	4.3	18	24
20,000	3.5	5	24	31
25,000	4.5	5.8	31	40
30,000	5.5	6.6	42	50
35,000	6.5	7.6	54	65
40,000	7.5	8.8	72	88
45,000	8.5	10	95	116
50,000	9.6	12	128	160
55,000	11	14	170	222
60,000	13	16	230	295
65,000	16	19	300	400
70,000	20	23	400	570
75,000	25	27	525	...
80,000	31	34	700	...
85,000	40	44	...	...
90,000	51	57	...	...
95,000	67	75	...	...
100,000	91	100	...	...
105,000	137	160	...	...
110,000	290	325	...	...
115,000	500	550	...	...
120,000	700	750	...	...
125,000	900	950	...	...
130,000	1100	1150	...	...

part of the circuit under consideration. In this manner the values of at_m and at_a in **(37)** can be obtained, the former by one single operation if the field frame is all of the same material, or by adding several products if various portions of the magnet frame are made of different materials.

The exact calculation of the compensating ampere-turns, at_r, is shown in Par. **65**; for preliminary calculation of the magnetizing force, however, it is sufficient to increase the sum of the gap, armature, and frame ampere-turns by *15* or *20* per cent., to make up the demagnetizing tendency due to armature reaction.

64. Magnetization Curves.—In Fig. 27 the magnetization curves are given for *cast iron, wrought iron,* and *cast steel,* the values being averaged from tests of various brands of each kind of iron. These curves are well adapted for the student's use, but the practical dynamo designer will obtain closer results by using curves plotted particularly for the iron which he employs. For the convenience of the student the values contained in Fig. 27 are given in Table **26.**

65. Magnetizing Force for Compensating Armature Reactions.—The armature current, in magnetizing the armature core, exerts a double influence upon the magnetic circuit: (1) a *direct* weakening influence upon the magnetic field, due to the lines of force set up by the armature winding, and (2) an *indirect,* secondary influence by shifting the magnetic field in the direction of the rotation in case of a generator, and in the opposite direction in case of a motor, thereby causing greater magnetic density to take place in those portions of the polepieces at which the armature leaves the pole than in those at which it enters.

The *direct* weakening effect of the armature current, or the number of field ampere-turns which are neutralized by the influence of the armature current, is equal to the *back* *ampere-turns*, or those within the demagnetizing belt; see Par. **61,** Book **15.** This demagnetizing number of ampere-turns is equal to $\frac{1}{360}$ of the total armature turns multiplied by twice the angle of the brush lead, or:

$$at_r' = \frac{N' \times C}{2n_p} \times \frac{\alpha}{180}, \dots\dots\dots\dots\dots\dots (44)$$

in which N' = total number of turns on armature;
C = current flowing in armature;
$2n_p$ = number of parallel armature circuits;
α = angle of field distortion, or angle of brush lead.

The number of armature turns, N', is equal to the number of armature conductors, N, in case of *ring-wound* armatures, and equal to one half the number of conductors in case of *drum-wound* armatures.

The angle of field distortion in a *smooth-core* armature is approximately equal to half the angle between two adjacent pole corners. In *toothed* and *perforated* machines, the weakening effect of the armature magnetomotive force is checked by the presence of iron surrounding the conductors, this checking influence being the stronger the greater the ratio of tooth section to field density, that is, the smaller the tooth density. The angle of lead in *toothed* armatures is from *.3* to *.9* times the half-pole-angle, and for *perforated* machines from *.2* to *.8* times that angle, according to the flux density in the teeth. For the tooth densities usually employed in practical machines, the above formula (**44**) should be multiplied by ½ or ⅔ for toothed armatures, and by ⅓ or ½ for *perforated* armatures.

The *indirect* influence of the armature field, due to the greater magnetizing force required on account of the increased flux density in the armature teeth and polepieces, depends upon the material of, and the average density in, the polepieces. The number of ampere-turns required to compensate for the indirect effect is usually from *25* to *100* per cent. of direct compensating ampere-turns; hence, the total number of compensating ampere-turns is from 1.25 to 2 times the direct compensating ampere-turns and can therefore be expressed by the formula:

$$at_r = k \times \frac{N' \times C}{2n_p} \times \frac{\alpha}{180}, \dots\dots\dots\dots\dots\dots (45)$$

in which k is a factor which usually varies from *1.25* to *2.00*, as follows:

k = 1.25 to 1.75, *average 1.5,* for *wrought iron* and *cast steel* polepieces;
k = 1.50 to 2.00, *average 1.75,* for *cast iron* polepieces.

The average of k for *wrought iron* and *cast steel* corresponds to a mean flux density of about 105,000 lines per square inch; the lower limit is for 80,000 lines, or less, and the upper figure given refers to a density of about 120,000 lines per square inch. For *cast iron* the average corresponds to a mean density in the polepieces of about 45,000 lines per square inch; the minimum corresponds to 20,000 lines, or less. and the maximum is to be taken when the average density in the polepieces is about 60,000 lines per square inch.

66. Calculation of Ampere-Turns for Bipolar Smooth-Armature Dynamo.—The various dimensions of the magnetic circuit of the machine represented at the right in Fig. 25 having been determined, the ampere-turns required in the field coils are calculated as follows:

The number of ampere-turns needed to overcome the reluctance of the two air gaps is obtained from (**42**), in which for the present case $\mathbf{B}_g{}''$ = 30,500 lines per square inch (see page 72), and $l_g{}''$ = 2 × ½ × 1.25 = 1¼ inches. The average length of the magnetic lines in the gaps is here taken 25 per cent. greater than twice the distance across from polepiece to armature core, because. when the machine is carrying current in the armature, the lines do not pass straight across in the direction of the radius, but are more or less inclined to the latter, owing to the distortion of the field. We therefore have:

$$at_g = .313 \times 30{,}500 \times 1\tfrac{1}{4} = 11{,}930 \text{ ampere-turns.}$$

The ampere-turns needed to overcome the armature reluctance are obtained from (**43**). In order to find the average length, l_a', of path for the lines in the armature, the longest line, *FG*, and the shortest line, *TU*, are drawn as indicated by dotted lines in Fig. 25. The average length, *VW*, is then laid off midway between them. In Fig. 25 the lines *FG*, *TU*, and *VW* are not continuous, because the armature shown to the left, being a toothed armature, has a smaller internal diameter than that on the right, which is a smooth armature. In the present case the right side of Fig. 25 is to be considered only; in speaking of lines *FG*, *TW*, and *VW*, therefore, the left half of the armature is supposed to be symmetrical to the right half, so that the dotted lines in the two halves meet at the center line. By measuring the continuous line *VW* so obtained, the average length of the path in the armature is found to be about 11 inches. The flux density in the armature core was taken at 80,000 lines per square inch (see page 75); the specific magnetizing force for wrought iron having this density is $\mathbf{H}_a'' = 31$ ampere-turns per inch, according to Fig. 27 or to Table **26**. Consequently, the armature magnetizing force:

$$at_a = 31 \times 11 = 340 \text{ ampere turns.}$$

The ampere-turns needed to overcome the field magnet reluctance are calculated by substituting in (**43**) the respective values of l_m'' and $\mathbf{H}_m'$ for the magnet frame. The length of path, *HXE*, Fig. 25, is found by measurement to be about 59 inches. The flux density $\mathbf{B}_m''$ was fixed at 90,000 lines per square inch (see page 72), for which the specific magnetizing force, by Table **26**, is $\mathbf{H}_m'' = 51$, the material of the cores and yoke being wrought iron. Hence,

$$at_m = 51 \times 59 = 3{,}010 \text{ ampere-turns.}$$

The compensating ampere-turns, since the average density in the wrought iron polepieces is less than 80,000 lines per square inch, are, according to formula (**45**),

$$at_r = 1.25 \times \frac{125 \times 240}{2} \times \frac{22\frac{1}{2}}{180} = \mathit{2{,}350} \text{ ampere-turns.}$$

It is here assumed that the machine under consideration is a generator of about 125 volts and 240 amperes output, the number of armature conductors being determined by transposing formula (**21**), page 41, thus:

$$N = \frac{6 \times 10^9 \times n_p \times E}{\Phi \times n_1} = \frac{6 \times 10^9 \times 1 \times 125}{5{,}000{,}000 \times 1200} = 125.$$

The pole space angle, in laying out Fig 25, was assumed to be 180° − 135° = 45°, half of which is taken as the angle of brush lead in the above formula.

Summing up the above magnetizing forces, according to (**37**), we obtain:

$at_g = 11{,}930$ ampere-turns for air gaps;
$at_a = 340$ " " armature;
$at_m = 3{,}010$ " " magnet frame;
$at_r = 2{,}350$ " " armature reaction.
$AT =$ **17,630**, total ampere turns required.

67. Calculation of Ampere-Turns for Bipolar Toothed-Armature Dynamo.

—The calculation in Par. **66** applies to a *smooth* armature; if a *toothed* core armature were adopted, the required magnetizing force would be less, as follows:

The air gap is smaller in a toothed machine, being $\frac{1}{8}$ inch in the present case instead of $\frac{1}{2}$ inch. The length of the path in air, therefore, is $\frac{1}{4}$ inch for the toothed armature. The gap density, however, is greater if the armature flux remains the same, owing to the concentration of the lines by virtue of the teeth. Adding about 50 per cent. to the previous value of the gap density, we obtain $\mathbf{B}_g'' = 45{,}000$ lines per square inch. Hence, we find that the gap magnetizing force for the toothed armature is:

$$at_g = .313 \times 45{,}000 \times \tfrac{1}{4} = \mathit{3{,}520} \text{ ampere-turns.}$$

The cores are only 9 inches long instead of $13\frac{1}{2}$, hence, the path in the frame is 9 inches shorter, or $l_m'' = 50$ inches, and we have:

$$at_m = 51 \times 50 = \mathit{2{,}550} \text{ ampere-turns.}$$

The compensating ampere-turns are also less in the case of a toothed armature, since the angle of field distortion is smaller; taking $\alpha = 12°$, we obtain:

$$at_r = 1.25 \times \frac{125 \times 240}{2} \times \frac{12°}{180} = \mathit{1{,}250} \text{ ampere-turns.}$$

The number of armature ampere-turns, however, is greater for a toothed than for a smooth armature, because the flux in the teeth is higher than that in the solid portion of the core. Assuming a tooth density of 120,000 lines per square inch, which is often employed, the specific magnetizing force for the teeth would be 700 ampere-turns per inch (see Table **26**), and if the slots are 1 inch deep the tooth ampere-turns would be:

$$at_a' = 700 \times 2 = \mathit{1{,}400} \text{ ampere-turns.}$$

For the remaining 9 inches of the path, the flux density is 80,000 lines per square inch, as before, hence the magnetizing force required for the solid portion of the armature core

$$at_a'' = 31 \times 9 = \mathit{280} \text{ ampere-turns.}$$

The total number of armature ampere-turns for the toothed armature, therefore, is:

$$at_a = 1{,}400 + 280 = \mathit{1{,}680} \text{ ampere-turns,}$$

instead of 340, as in the case of the smooth armature.

The total magnetizing force required in case of the toothed armature, consequently, is:

$$AT = 3{,}520 + 2{,}550 + 1250 + 1{,}680 = \mathbf{9{,}000} \text{ ampere-turns,}$$

as against *17,630* ampere turns for the smooth-armature machine.

68. Calculation of Ampere-Turns for Four-Pole Smooth-Armature Dynamo.

—Referring to Fig. 26, the mean lengths of the path for the smooth-armature design are as follows: $l_g'' = 1.25$ inches (the gap distance of $2 \times \frac{1}{2}$ inch being increased by 25 per cent. to allow for distortion), $l_a'' = 6$ inches, and $l_m' = 33$ inches. The pole space angle in this case is $22\frac{1}{2}°$, one-half of which is about 11°. Therefore, the magnetizing forces required in the different parts of the circuit:

$$\begin{array}{llll}
at_g & = .313 \times 30{,}500 \times 1.25 & = 11{,}930 & \text{ampere-turns;} \\
at_a & = 31 \times 6 & = 190 & \text{"} \\
at_m & = 51 \times 33 & = 1{,}680 & \text{"} \\
at_r & = 1.25 \times \dfrac{125 \times 2 \times 240}{4} \times \dfrac{11°}{180} & = 1{,}150 & \text{"} \\
\multicolumn{2}{r}{\text{Total magnetizing force: } AT =} & \overline{\mathbf{14{,}950}} & \text{"}
\end{array}$$

In the formula for at_r, the number of turns must here be multiplied by 2, because in a four-pole machine there are 4 parallel armature circuits, hence in formula (**21**) the number of pairs of circuits has the value $n_p = 2$.

69. Calculation of Ampere-Turns for Four-Pole Toothed-Armature Dynamo.—For the toothed-armature design the lengths are $l_g' = \frac{1}{4}$ inch, $l_a' = 7\frac{1}{2}$ inches, and $l_m' = 26$ inches; and the angle of brush lead is about 6°; hence, we have:

$$\begin{array}{lllll}
at_g & = .313 \times 45{,}000 \times \frac{1}{4} & = 3{,}520 & \multicolumn{2}{l}{\text{ampere-turns;}} \\
at_a' & = 700 \times 2 & = 1{,}400 & \text{"} & \text{"} \\
at_a'' & = 31 \times 5\frac{1}{2} & = 170 & \text{"} & \text{"} \\
at_m & = 51 \times 26 & = 1{,}330 & \text{"} & \text{"} \\
at_r & = 1.25 \times \dfrac{250 \times 240}{4} \times \dfrac{6}{180} & = 630 & \text{"} & \text{"}
\end{array}$$

Total magnetizing force: $AT = \overline{\mathbf{7{,}050}}$ ampere-turns.

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THE DESIGN OF DIRECT-CURRENT DYNAMOS AND MOTORS.

CALCULATION OF MAGNET WINDING.

70. Series, Shunt, Compound, and Differential Field Winding.—Having found the total number of ampere-turns required to cause the necessary flux through the magnet frame, the final calculation of the field winding consists in determining the proper number of turns and amperes which, when multiplied together, will produce the desired magnetizing force. The determination of the strength of the current passing through the field winding, and, consequently, the selection of the size of the field wire, depends upon the method of field excitation employed.

There are four methods of winding the magnets of continuous-current machines, the *series, shunt, compound,* and *differential winding,* each of which has distinct advantages which make its use preferable for certain purposes.

Series winding is used chiefly for constant-current arc-light generators and for street railway motors, but in the latter case, though the field winding as a whole is in series with the armature, the separate coils can be variously connected in series or in parallel with each other, so as to vary their resistance and magnetizing effect. Series winding is sometimes adopted for motors applied to hoisting and other purposes where very variable speed is required. Series motors may also be used for driving fans, pumps, or other machines in which the load is fairly constant and is positively connected by direct coupling or gearing, so that the motor speed cannot become excessive, as it would tend to do if a belt slipped off.

Shunt winding is almost universally employed in motors for constant speed with variable load. Shunt-wound generators were formerly used for giving constant voltage for electric light, power, and railway purposes, but at present *compound-wound generators* have largely taken their place, since the latter automatically maintain a constant, or even slightly rising, voltage with increase of load.

Compound winding, besides being used for most generators, is further applied to motors when a strong starting torque is required.

Differential winding is applicable to generators that are required to produce a fairly constant voltage with wide variations in speed, as, for example, those driven by windmills, or by the axles of railway cars for electric train lighting. Differential winding is also employed in motors required to run with very constant speed at varying load.

In any given case there is generally little difficulty in deciding which of the four methods of field winding should be adopted, the custom being well defined regarding generators and motors for each purpose.

71. Determination of the Magnet Winding.—The method of winding being decided upon, the next step is to find the proper size of wire to employ for the field coils. It is obvious that a given number of ampere-turns may consist of a few turns carrying a large current, or of a great number of turns carrying a small current.

Whether the former or latter arrangement is employed depends upon the method of field excitation of the dynamo. In a *series machine* the total armature current traverses the field coils; hence the field winding consists of few turns of a conductor having a comparatively large current capacity. In a *shunt dynamo*, on the other hand, only a very small portion of the total current flows through the field winding; the latter must, therefore, consist of many turns of fine wire. *Compound* and *differential machines*, finally, have a series winding as well as a shunt winding, *assisting* each other in the former, and *opposing* each other in the latter; the total excitation, therefore, is the *sum* of the series and shunt ampere-turns in one case, and their *difference* in the other. The methods employed for determining the number of turns and the size of wire for the various kinds of field windings are given in the following paragraphs **72** to **74.**

72. Calculation of Series Winding.—The field winding of a series machine being always fed by the total current generated or supplied, which has a definite value, the required number of turns, T, is immediately found by dividing the ampere-turns, AT, by the given value, C, of the current; thus:

$$T = \frac{AT}{C} \tag{46}$$

The size of wire must be sufficient to carry the given current C without overheating and without causing an undue loss of power in the magnets. This condition is usually fulfilled by providing a conductor area of from *1,000* to *2,000* circular mils per ampere. For series dynamos furnishing a constant current of 10 amperes, the usual current output of series arc-lighting machines, the size of the magnet wire has been found by experience to be between $\frac{1}{10}$ and $\frac{1}{8}$ inch in diameter—that is, No. *10*, No. *9*, or No. *8* B. & S. gauge, depending upon the depth of the winding and the temperature limit prescribed. For the usual range of temperature rise employed, which is from *20°* to *50°* C., the specific cooling surface of the magnet coils should be from 4 to 1½ square inches per watt, respectively, as follows:

For a rise of 20° C. allow about 4 square inches per watt;
" " " " 25° " " " 3½ " " " "
" " " " 30° " " " 3 " " " "
" " " " 40° " " " 2 " " " "
" " " " 50° " " " 1½ " " " "

73. Calculation of Shunt Winding.—In the determination of the best size of wire for a shunt winding, the quantities known are the ampere-turns required and the voltage by which the shunt winding is supplied—that is, the voltage of the machine. One of the simplest methods is based upon the fact that the resistance of one mil-foot of commercial copper—that is, the resistance of one foot of a copper wire, one mil, or one-thousandth of inch, in diameter—is almost exactly 12 ohms at 60° C., which is about 35° C. above the average machine-room temperature. Hence, the resistance of any conductor of commercial copper at 60° C. is

$$R = \frac{12 \times l'}{d^2},$$

in which l' is the length of the wire, in feet, and d^2 its sectional area in circular mils. Or, since $12 \times l'$ is the length of the wire in inches, we can write

$$R = \frac{l''}{d^2}, \qquad \ldots\ldots\ldots\ldots\ldots\ldots (47)$$

in which l'' is the length of the wire *expressed in inches.* The current flowing in the above wire is, by Ohm's Law,

$$C = \frac{E}{R} = \frac{E \times d^2}{l''}.$$

It is also evident that the ampere-turns in any shunt winding are numerically equal to the amperes that would result if a single turn of the magnet wire were supposed to be subjected to the given voltage, because two turns would have twice the resistance and take one-half the current; three turns would have three times the resistance and therefore take one-third the current; and so on for any number of turns. Since the current flowing in a shunt circuit is the terminal E. M. F. divided by the shunt resistance, we have therefore:

$$\text{Ampere-turns} = \frac{\text{Voltage}}{\text{Resistance of One Turn}}.$$

Expressing the resistance according to formula (47), this becomes:

$$\text{Ampere-turns} = \frac{\text{Voltage} \times \text{Circular Mils}}{\text{Length of One Turn in inches}},$$

or in symbols:

$$AT = \frac{E \times d_m^2}{l_t''}, \quad \ldots\ldots\ldots\ldots\ldots\ldots (48)$$

where E = terminal voltage of machine;
d_m = the diameter of the magnet wire, in mils;
and l_t' = mean length of one turn, in inches.

By transposition of (**48**) we obtain the cross-section of the magnet wire required:

$$d_m^2 = \frac{AT \times l_t''}{E'}, \quad \ldots\ldots\ldots\ldots\ldots\ldots (49)$$

in which AT = total magnetizing force required, in ampere-turns;
l_t' = average length of one turn of wire in magnets, in inches;
E' = voltage between terminals of shunt winding.

In applying the above formula to a shunt winding for a generator, allowance must be made for the resistance of the rheostat, which is put in the shunt circuit to regulate the E. M. F. This resistance will consume a portion of the voltage amounting to from 10 to 20 per cent. Therefore, the voltage E' substituted in the formula should be 10 to 20 per cent. lower than the E. M. F. of the machine.

For a multipolar machine, E' in the above formula is the voltage corresponding to *one set* of coils. Thus, if all the coils are connected *in series*, and if there are *two* coils in each magnetic circuit, the value of E' in a *four-pole* machine is *one-half* the machine-voltage (diminished by 10 or 20 per cent. in case of a generator); in a *six-pole* machine, E' is *one-third;* in an *eight-pole* dynamo, *one-fourth* of the terminal voltage, etc. In the case that the field coils are connected *in groups* across the machine terminals, the proper value of E' is found by multiplying the number of coils constituting one magnetic circuit by the number of parallel groups, and dividing the product so obtained by the total number of coils on the machine; the result is the factor by which the terminal voltage of the machine must be multiplied. For example, if the shunt winding of a 12-pole ring type 125-volt generator is connected in 4 groups of 3 magnets each, the above factor will be $\frac{2 \times 4}{12} = \frac{2}{3}$, hence $E' = \frac{2}{3}(125 - 12\frac{1}{2}) = 75$ volts. If in the same machine all the magnets were connected in parallel, that is to say, if the number of groups were 12, we would have $\frac{2 \times 12}{12} = 2$, and the shunt voltage per magnetic circuit would be $E' = 2 \times 112\frac{1}{2} = 225$ volts.

The size of wire obtained by formula (**48**) will furnish the required number of ampere-turns irrespective of the number of turns employed. If a small number of turns is chosen, the current will be high; and if a large number of turns is used, the current will be small. If the current is too high, the wire will become overheated and may eventually burn out. If the shunt current is taken too small, the magnet winding will become too bulky and the cost of the machine unnecessarily great in consequence. It is therefore seen that it is very important to determine the proper strength of the shunt current in each case.

Designating the watts consumed in the magnet winding by w_m, the shunt current can be expressed as

$$C_{sh} = \frac{w_m}{E'}.$$

Since in this equation E' is known, being the terminal voltage of the machine diminished by 10 to 20 per cent. to allow for the drop due to the regulating resistance, the problem remains to find the proper value of w_m. The power which can be dissipated in the field winding depends upon the cooling surface of the magnets and upon the temperature rise permitted. If the cooling surface of the magnet coils is denoted by S_M, and the allowable temperature increase by t, in Centigrade degrees, the power dissipated in the magnet winding is given by

$$w_m = \frac{t}{75} \times S_M. \quad \text{...............} \quad \textbf{(50)}$$

the average temperature increase with a power dissipation of 1 watt per square inch of exposed coil surface being about 75° C.

Inserting the value of w_m given by **(50)** into the above equation for C_{sh}, the following formula for the shunt current is obtained:

$$C_{sh} = \frac{t \times S_M}{75 \times E'}, \dots\dots\dots\dots\dots \text{(51)}$$

in which t = prescribed temperature increase of magnets, in degrees C., being usually limited to 50°;

S_M = cooling surface of magnets, in square inches.

The values of l_t and S_M, in formulas **(49)** and **(51)** respectively, depend upon the height of the magnet winding, which at this stage of the calculation is not yet known. We must, therefore, temporarily make an assumption of its magnitude. For this purpose the average practical height of the winding on magnets of different sizes is given in Table **27**, page 98. The winding height of a *cylindrical* magnet is obtained by taking the figure given under the heading of "*Circular Cores*" for the nearest diameter given in the first column. In case of a *rectangular* or *oval* magnet, the figure corresponding to the nearest cross-section given in the second column is taken. Thus, to find the height of the winding space of a rectangular magnet, *4* by *6* inches, the nearest area given in the second column is *28.3* square inches; hence, the required winding height is *2* inches in case of a bipolar machine, and *2¼* inches in case of a multipolar machine.

The two columns added at the right give the ratios of the length of the mean turn to that of the diameter, and, of course, only apply to circular magnets. These ratios are tabulated in preference to the actual lengths of the average turn, in order to enable the ready application of the table to diameters intermediate to those given. The approximate length of the mean turn for a cylindrical magnet of any diameter between 1 and 36 inches can be directly taken from the table by multiplying the diameter of the core under consideration by the ratio given for the nearest diameter in the respective one of the two last columns. For instance, if the diameter of the core is 6⅝ inches, the ratios for the 6-inch core are taken and the mean turn is found:

$$l_t' = 6\tfrac{5}{8} \times 3.93 = \mathbf{26} \text{ inches,}$$

if the machine is of a *bipolar* type; and

$$l_t' = 6\tfrac{5}{8} \times 4.32 = \mathbf{28.6} \text{ inches,}$$

in case of a *multipolar* type.

TABLE 27.

HEIGHT OF WINDING SPACE FOR DYNAMO MAGNETS.

Size of Magnet Core.		Height of Winding Space, inches.				Ratio of Mean Turn to Diameter of Circular Cores.	
		Circular Cores.		Rectangular or Oval Cores.			
Diameter, inches.	Cross-Section, sq. ins.	Bipolar.	Multipolar.	Bipolar.	Multipolar.	Bipolar.	Multipolar.
1	.8	½	¾	..	..	4.71	5.50
2	3.1	¾	1¼	1	1½	4.32	5.11
3	7.1	1	1¾	1¼	2	4.19	4.97
4	12.6	1¼	2	1½	2½	4.12	4.71
6	28.3	1½	2¼	2	2¾	3.93	4.32
8	50.3	1¾	2½	2½	3	3.83	4.12
10	78.5	1⅞	2¾	2¾	3¼	3.73	4.01
12	113.1	2	3	3	3½	3.66	3.93
15	176.7	2⅛	3¼	3¼	3¾	3.59	3.82
18	254.5	2¼	3½	3½	4	3.54	3.75
21	346	2⅜	3¾	3¾	4½	3.50	3.70
24	452	2½	4	4	5	3.47	3.67
27	573	2⅝	4¼	4¼	5½	3.45	3.64
30	707	2¾	4½	4½	6	3.43	3.62
33	855	2⅞	4¾	5	6½	3.41	3.60
36	1018	3	5	5½	7	3.40	3.58

74. Calculation of Compound Winding.—In a compound dynamo the series winding supplies the excitation necessary to produce a potential equal to that lost by armature and series field resistance and by armature reaction. Therefore, the number of shunt ampere-turns for a compound wound machine is the magnetizing force needed *on open circuit,* and the number of series ampere-turns required to maintain constant voltage is the *difference* between the excitation needed for *normal load* and that on *open circuit.* The proper number of shunt and series ampere-turns is computed as follows:

The flux, Φ_0, required on open circuit is that number of lines of force which will produce the no-load or terminal E. M. F., E_0, of the dynamo, or, by formula (**21**), page 41:

$$\Phi_0 = \frac{6 \times 10^9 \times n_p \times E_0}{N \times n_1};$$

hence, the number of shunt ampere-turns needed to overcome, *on open circuit,* the reluctances of air gaps, armature core, and magnet frame, is:

$$AT_0 = at_{g_0} + at_{a_0} + at_{m_0}, \ldots\ldots\ldots\ldots (\mathbf{52})$$

in which the magnetizing forces of the various portions of the magnetic circuit are computed with reference to the flux densities corresponding to the above no-load flux Φ_0. The compensating ampere-turns are missing from this formula, because there is no armature reaction on open circuit, as no current flows in the armature.

The armature flux at normal load is:

$$\Phi = \frac{6 \times 10^9 \times n_p \times E}{N \times n_1},$$

where E is the total E. M. F. of the dynamo at normal load.

The total ampere-turns needed for excitation at normal load, therefore, are obtained by computing AT from formula (**37**), page 79, using the flux densities corresponding to the normal flux Φ. Since AT is supplied by the combined effect of the shunt and series winding, the difference between AT and AT_0 must be the number of series-ampere turns required, or

$$AT_{se} = AT - AT_0 \ldots\ldots\ldots\ldots\ldots (\mathbf{53})$$

The total E. M. F. of an *ordinary compound dynamo* is:

$$E = E_0 + 1.25 \times C \times r_a, \ldots\ldots\ldots (\mathbf{54})$$

where C is the current output and r_a the armature resistance of the machine, it being here assumed as an approximation that the series field resistance is $\frac{1}{4}$ of the armature resistance, which is an ample allowance.

In case the machine is to be *over-compounded* for loss in the line, the percentage of drop—usually 5 per cent.—is to be included into the output E. M. F.; hence the total E. M. F. generated at normal load, for 5 per cent. over-compounding, is

$$E = 1.05 \times E_0 + 1.25 \times C \times r_a. \ldots (\mathbf{55})$$

After having determined the number of shunt and series ampere-turns giving the desired regulation, the calculation of the compound winding merely consists in the respective application of the methods given in Pars. **72** and **73.**

The number of turns in the series field coils is AT divided by the normal current of the machine, which is known. The large conductors needed for the series coils of compound dynamos should have a cross-section of 1,000 to 1,500 circular mils per ampere.

In calculating the number of shunt turns, the total allowable power dissipation, w_m, in the magnets must be diminished by the power dissipated in the series winding, which can be easily computed by multiplying the square of the current by the series field resistance. If the shunt dissipation so remaining is found too small to obtain a practical number of shunt turns, the size of the series wire must be increased in order to reduce the series resistance and thus to allow more power dissipation for the shunt winding.

In the calculation of a *differential winding*, the proceeding is practically the same as in a compound winding. The only difference between the two is that in a differential winding, since the series coils are wound *in opposition* to the shunt coils, AT_0 is greater than AT, hence AT_s becomes negative.

The calculation of magnet windings by means of formulas (**37**) to (**55**), respectively, is best understood by applying them to specific cases.

75. Data for Magnet Winding.—Table **28**, page 102, gives the areas, the usual diameter, the number of turns per inch, and the weight and resistance of insulated magnet wire. Magnet wires, except the large sizes down to No. 3, are usually insulated by a single cotton covering (S. C. C.), the large sizes being double cotton covered. This table is intended to be employed in calculating magnet windings, and its use will be seen from the following paragraphs.

76. Determination of Series Field Winding for Bipolar Smooth-Armature Machine.—To show the application of the method given in Par. **72**, let us assume that the machine represented in Fig. 25 is a 35 H. P. series motor to be supplied with 500 volts and 65 amperes. The ampere-turns required for compensating armature reaction, though in this case not exactly the same as determined in Pars. **66** and **67**, are approximately correct, because the number of turns for 500 volts must be increased in about the same proportion as the current strength in them is reduced. In taking the total number of ampere-turns as obtained above, no serious error is therefore committed.

The number of turns is obtained by dividing the total number of ampere-turns by the current, which is 65 amperes. In case of the smooth-armature design, AT was found 17,630 ampere-turns; therefore, by (**46**),

$$T = \frac{17630}{65} = \mathbf{272} \text{ turns.}$$

TABLE 28.

DATA OF BARE AND INSULATED MAGNET WIRE.

1	2	3	4	5	6	7	8
Size, B. & S.	Diam. inches. Bare Wire.	Area, Cir. Mils. Bare Wire.	Diam. of S. C. C. Wire.	Number of turns per inch. S. C. C.	Lbs. per foot, Bare Wire.	Lbs. per foot, S. C C. Wire.	Ohms per foot at 20° C.
1	.289	83,521	.309 [1]	3.28 [1]	.2533	.259 [1]	.000124
2	.258	66,564	.278 [1]	3.59 [1]	.2009	.206 [1]	.000156
3	.229	52,441	.249 [1]	4.01 [1]	.1593	.168 [1]	.000197
4	.204	41,616	.216	4.63	.1264	.1292	.000248
5	.182	33,124	.194	5.16	.1002	.1023	.000313
6	.162	26,244	.172	5.82	.0795	.0812	.000394
7	.1443	20,822	.154	6.5	.0630	.0645	.000497
8	.1285	16,512	.139	7.2	.0500	.0512	.000627
9	.1144	13 087	.124	8.1	.0396	.0406	.000791
10	.10190	10,384	.112	8.9	.0314	.0323	.000992
11	.09074	8,234	.101	9.9	.0249	.0257	.00126
12	.08081	6,530	.088	11.4	.0198	.0203	.00159
13	.07196	5,178	.079	12.7	.0157	.0161	.00200
14	.06408	4,106	.071	14.1	.0124	.0128	.00252
15	.05707	3,257	.064	15.6	.0099	.0103	.00318
16	.05082	2,583	.058	17.3	.0078	.0081	.00401
17	.04526	2,048	.050	20.0	.0062	.0064	.00506
18	.04030	1,624	.045	22.2	.0049	.0051	.00638
19	.03589	1,288	.041	24.4	.0039	.0041	.00804
20	.03196	1,021	.037	27.0	.0031	.00325	.01014
21	.02846	810	.033	30.3	.00245	.00260	.01275
22	.02535	643	.030	33.3	.00195	.00209	.01608
23	.02257	509	.028	35.7	.00154	.00164	.02030
24	.02010	404	.025	40.0	.00122	.00133	.02560
25	.01790	320	.023	43.5	.00097	.00106	.03225
26	.01594	254	.021	47.7	.00077	.00085	.04075
27	.01420	202	.019	52.6	.00061	.00068	.05135
28	.01264	160	.017	58.8	.000484	.00054	.0648
29	.01126	127	.015	66.7	.000384	.00043	.0818
30	.01003	101	.014	71.4	.000304	.00034	.1030

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[1] Double Cotton Covered.

Allowing 1,250 circular mils per ampere, the cross-section of the wire is found:

$$1{,}250 \times 65 = \mathbf{81{,}250} \text{ circular mils,}$$

which is slightly less than the sectional area of No. *1* B. & S. wire. As this size of wire would ordinarily be rather clumsy to handle, it is better to use several smaller conductors in parallel. For example, we find in Table **28**, page 102, that *three No. 6* wires have a combined sectional area of 3 × 26,244 = 78,732 circular mils, which is slightly smaller than found above and gives about 1,210 circular mils per ampere. No. 6 S.C.C. wire has a diameter of .172 inch.

Since the magnet core for the smooth-armature machine is 13½ inches long, the actual length of the winding space will be about 12½ inches, when allowing for end discs and insulation of the spool ends. The number of turns per layer is therefore 12½ ÷ .172 = 72, and, since for three wires in parallel the total number of turns is 3 × 272 = 816, or 408 on each core, there must be 408 ÷ 72 = 6 layers of No. 6 wire in each coil. The height of winding will therefore be 6 × .172 = 1⅛ inches, allowing for core insulation.

The diameter of the core being 10 inches, the average length of one turn is:

$$l_t'' = (10 + 1\tfrac{1}{8}) \times \pi = 35 \text{ inches, or } 2.92 \text{ feet.}$$

There are 408 ÷ 3 = *136* turns of each wire on each core- the length of each No. 6 wire per core, therefore, is 136 × 2.92 = *397* feet, and its resistance at 20° C., from Table **28**, is 397 × .000394 = *.156* ohm. Since there are three of these wires in parallel and two coils in series, the combined resistance of the two magnets at 20° C. is

$$(.156 \div 3) \times 2 = \mathbf{.104} \text{ ohm.}$$

The working temperature may be taken as 60° C., that is, 25° C. plus the average rise of 35° C., and since the increase in resistance is about .4 per cent. for each rise of one degree C., the resistance will become 35 × .4 = 14 per cent. greater, that is,

$$.104 \times 1.14 = \mathbf{.12} \text{ ohm.}$$

The current being 65 amperes, the drop in the field winding is $65 \times .12 = \mathit{7.8}$ volts, which is $7.8 \div 500 = .0156$, or 1.56 per cent. of the voltage supplied, being a moderate amount.

The power loss in the series field coils is

$$65^2 \times .12 = \mathit{507} \text{ watts.}$$

The cylindrical surface of each coil is:

$$(10 + 2 \times 1\tfrac{1}{8}) \times \pi \times 12\tfrac{1}{2} = 480 \text{ square inches.}$$

It is proper, also, to consider the ends of the coils as part of the cooling surface, each of them being

$$11\tfrac{1}{8} \times \pi \times 1\tfrac{1}{8} = 39 \text{ square inches.}$$

This makes a total surface of $480 + 78 = 658$ square inches for one coil, or *1,316* square inches for both. The specific cooling surface of the field winding is, therefore:

$$1{,}316 \div 507 = \mathbf{2.6} \text{ square inches per watt,}$$

which is within the practical limits. If the number of square inches per watt is found below 1½, the coil should be wound with the next larger size wire, which would decrease the power loss and increase the cooling surface, thereby augmenting the number of square inches per watt.

77. Determination of Series Winding for Bipolar Toothed-Armature Machine.—The series winding for the toothed-armature core machine will be as follows: For the toothed-armature machine $AT = 9{,}000$ ampere-turns, hence the number of turns:

$$T = \frac{9.000}{65} = \mathbf{140}.$$

The cores being 9 inches long, the available space for the winding will be about 8¼ inches. Since the diameter of No. 6 magnet wire is .172 inch, each core can therefore be wound with $8\tfrac{1}{4} \div .172 = 48$ turns of No. 6 wire. Taking again 3 strands of No. 6 wire, as in Par. **76**, the number of turns per core is $(140 \times 3) \div 2 = 210$, making the number of layers 210 ÷ 48 = 5. The corresponding winding depth is 5 × .172 = 1 inch, allowance being made for core insulation; and the mean turn, since the core diameter in this case is 10 inches, will be

$$l_t' = (10 + 1) \times \pi = 34.56 \text{ inches, or } 2.85 \text{ feet.}$$

The total resistance of the two series coils, since there are 3 times 70 turns of No. 6 wire in parallel in each core, is:

$$r_{se} = \frac{2 \times 70 \times 2.85 \times .000394}{3} = \mathbf{.0524} \text{ ohm at } 20° \text{ C.,}$$

$$\text{or} \qquad .0368 \times 1.16 = \mathbf{.061} \text{ ohm at } 60° \text{ C.}$$

The power loss in the magnet coils, therefore, is

$$65^2 \times .061 = 258 \text{ watts,}$$

while the cooling surface is:

$$S_M = (10 + 2) \times \pi \times 8\tfrac{1}{2} + 2 \times 34.56 \times 1 = 380 \text{ square inches per coil, or } \mathbf{760} \text{ square inches total.}$$

This makes the specific cooling surface

$$760 \div 258 = \mathbf{2.95} \text{ square inches per watt,}$$

which, according to Par. **72**, corresponds to a temperarise of 30° C.

78. Determination of Shunt Winding for Bipolar Smooth-Armature Motor.—Let the given motor be the same as considered in Par. **76**. For a shunt winding, the required size of wire is obtained from formula (**49**), in which, for the case of a motor, E' is usually the total supply voltage, a field rheostat being seldom employed with the ordinary motor. Substituting in (**49**) the value AT = 17,630 ampere-turns (as determined in Par. **66**), E' = 500 volts, and $l_t'' = 10 \times 3.73 = 37.3$ inches (from Table **27**), we obtain:

$$d_m^2 = \frac{17{,}630 \times 37.3}{500} = \mathbf{1{,}310} \text{ circular mils.}$$

The nearest size wire, according to Table **28**, is No. *19* B. & S., which has a diameter of .041 when insulated for use as magnet wire.

The approximate winding depth for a bipolar 10-inch core is found in Table **27** to be 1⅞ inches; the length of the coil space on each core is 12½ inches; hence, the total cooling surface of the two coils:

$$S_M = (10 + 2 \times 1\tfrac{7}{8}) \times \pi \times 12\tfrac{1}{2} \times 2 + 37.3 \times 1\tfrac{7}{8} \times 4 = \mathit{1{,}360} \text{ square inches.}$$

For a rise of 30° C., which we will assume to be prescribed in this case, we find by (**51**):

$$C_{sh} = \frac{30 \times 1{,}360}{75 \times 500} = \mathit{1.09} \text{ amperes.}$$

Dividing this into the number of ampere-turns, the required number of turns is obtained:

$$T = \frac{17{,}630}{1.09} = \mathit{16{,}200} \text{ turns, total, or } \mathit{8{,}100} \text{ turns per core.}$$

The number of wires that can be placed in one layer is 12½ ÷ .041 = 300; hence, the number of layers needed is 8,100 ÷ 300 = *27*. The actual height occupied by these 27 layers will be

$$27 \times .041 = 1.1 \text{ inches,}$$

making a winding depth of about 1¼ inches, which is considerably less than the height assumed above by the aid of Table **27**. Since for this height the cooling surface would be appreciably smaller than obtained above, the shunt current would have to be correspondingly smaller, which in turn would increase the number of turns, making the winding depth larger. Taking, therefore, a value between the two, or, say, 1½ inches, the cooling surface becomes:

$$S_M = (10 + 2 \times 1\tfrac{1}{2}) \times \pi \times 12\tfrac{1}{2} \times 2 + 11\tfrac{1}{2} \times \pi \times 1\tfrac{1}{2} \times 4 = \mathit{1{,}237} \text{ square inches,}$$

and we have:

Shunt current: $$C_{sh} = \frac{30 \times 1{,}237}{75 \times 500} = \mathbf{.99} \text{ ampere;}$$

Number of turns: $$T = \frac{17{,}630}{.99} = \mathbf{17{,}800};$$

Number of layers: $\frac{17.800}{2 \times 300} = \mathbf{30}.$

The height occupied by these 30 layers is

$$30 \times .041 = 1.24 \text{ inches},$$

which gives a winding depth of about 1½ inches, as taken above.

There being 30 layers of 300 turns each, or 9,000 turns in all, in each coil, the total length of wire in both coils is:

$$2 \times 9{,}000 \times \frac{11\frac{1}{2} \times \pi}{12} = 54{,}200 \text{ feet;}$$

hence, the shunt resistance at 20° C., according to Table **28**:

$$r_{sh} = 54{,}200 \times .00804 = \mathbf{436} \text{ ohms,}$$

which at 55° C. (25° + 30°) amounts to

$$r_{sh}' = 436 \times 1.14 = \mathbf{498} \text{ ohms.}$$

The actual shunt current is, therefore:

$$C_{sh} = \frac{500}{498} = \mathbf{1} \text{ ampere,}$$

which multiplied by the number of turns gives the actual excitation:

$$AT = 2 \times 9{,}000 \times 1 = \mathbf{18{,}000} \text{ ampere-turns.}$$

This is about 2 per cent. in excess of the magnetizing force needed.

The total weight of the insulated wire in both coils is, by Table **28**:

$$wt_m = 54{,}200 \times .0041 = \mathbf{222} \text{ pounds,}$$

or **111** pounds on each magnet.

Though not excessive, this is a somewhat greater weight of wire than would ordinarily be used on a machine of this kind. This is due to the fact that the length of the armature is rather small for a bipolar machine, but was so chosen in order to adopt the same armature for the 4-pole design as well. By increasing the length of the armature, the same length of conductor will occupy less height, thereby reducing the gap space and correspondingly diminishing the number of ampere-turns required.

79. Determination of Shunt Winding for Four-Pole Toothed-Armature Generator.—Inserting into (**49**) the value of the ampere-turns found in Par. **69** for the machine shown in Fig. 26, which in this case we will assume to be a 125-volt generator, we obtain

$$d_m^2 = \frac{7{,}050 \times 28.6}{\frac{1}{2}\,(125 - 25)} = \mathbf{4{,}030} \text{ circular mils.}$$

Herein 28.6 is the approximate mean length of one turn on a 6⅝-inch core for a multipolar machine, found from Table **27**, as shown on page 98. The factor ½ in the denominator indicates that in the present case the four magnets are to be connected in series (see Par. **73**). The deduction of 25 volts represents an allowance of 20 per cent. for regulating resistance.

The above value of d_m^2 is almost exactly the area of No. **14** B. & S. wire having a diameter of .071 inch when insulated (see Table **28**).

Using the value 2¼′ given in Table **27** for the average winding depth of a 6-inch multipolar magnet, and taking 3¼ inches as the available length of each winding space, the cooling surface is found:

$$S_m = (6\tfrac{5}{8} + 2 \times 2\tfrac{1}{4}) \times \pi \times 3\tfrac{1}{4} \times 2 + 28.6 \times 2\tfrac{1}{4} \times 2$$
$$= \mathit{355} \text{ square inches.}$$

In this case only one end surface of each coil is considered as cooling surface, because in a multipolar frame the polepieces cover up the inner ends. For a rise of 30° C., the shunt current is therefore obtained by (**51**), thus:

$$C_{sh} = \frac{30 \times 355}{75 \times 50} = \mathit{2.84} \text{ amperes,}$$

giving a specific cooling surface of

$$\frac{355}{50 \times 2.84} = \mathbf{2.5} \text{ square inches per watt.}$$

The number of turns required with the above shunt current is:

$$T = \frac{7{,}050}{2.84} = \mathbf{2{,}480}, \text{ or } \mathbf{1{,}240} \text{ turns per core.}$$

The total number of ampere-turns as found from formulas **(37)**, **(42)**, **(43)**, and **(45)** must in a multipolar ring machine be supplied to *each two cores*, as the various pairs of cores form a number of parallel magnetic circuits. In order to obtain a total number of AT ampere-turns, each of these parallel circuits must therefore be wound with AT ampere-turns.

Since the number of turns per layer is

$$3\tfrac{1}{4} \div .071 = \mathit{45},$$

there must be

$$1{,}240 \div 45 = \mathit{28} \text{ layers,}$$

making a winding depth of

$$28 \times .071 = \mathit{2} \text{ inches,}$$

not including the core-insulation, or about $2\tfrac{1}{8}$ inches total.

The resistance of the four magnet coils in series is:

$$r_{sh} = 4 \times 45 \times 28 \times \frac{(6\tfrac{5}{8} + 2\tfrac{1}{8}) \times \pi}{12} \times .00252$$
$$= \mathbf{29} \text{ ohms at } 20^\circ \text{ C.,}$$

or

$$29 \times 1.14 = \mathbf{33} \text{ ohms at } 55^\circ \text{ C.}$$

The actual shunt current required to produce the desired number of ampere-turns is:

$$C_{sh} = \frac{7{,}050}{2 \times 45 \times 28} = \mathbf{2.8} \text{ amperes;}$$

hence, the total resistance of the shunt circuit:

$$\frac{125}{2.8} = \mathbf{44.7} \text{ ohms,}$$

which makes the resistance of the regulating rheostat

$$44.7 - 33 = \mathbf{11.7} \text{ ohms.}$$

The weight of the magnet winding is:

$$wt_m = 45 \times 28 \times \frac{8\frac{3}{4} \times \pi}{12} \times .0128 = \mathbf{37} \text{ lbs. per core,}$$

or $$37 \times 4 = \mathbf{148} \text{ pounds, total.}$$

80. Determination of Compound Winding for Four-Pole Toothed-Armature Generator.—The machine considered in the preceding paragraph is to be compound wound for 5 per cent. over compounding; the temperature increase to be 35° C. The four series coils are to be connected in parallel, and the four shunt coils in two groups of two coils each.

We must first determine the respective numbers of shunt and series ampere turns. We assume the number of armature turns to be 250, and 125 to be the voltage on open circuit. Proceeding as indicated in Par. **74**, we then obtain the flux required on open circuit:

$$\Phi_o = \frac{6 \times 10^9 \times 2 \times 125}{250 \times 1,200} = \mathbf{5,000,000} \text{ lines,}$$

which is the number upon which the calculations in the previous paragraphs are based. The flux densities on open circuit are, therefore, the same as in Par. **69**, and in this case we have:

For air-gaps: $\mathbf{B}_{g_o}'' = 45,000$; $\mathbf{H}_{g_o}'' = .313 \times 45,000$

" armature teeth: $\mathbf{B}_{a_o}' = 120,000$; $\mathbf{H}_{a_o}' = 700$

" armature core: $\mathbf{B}_{a_o}'' = 80,000$; $\mathbf{H}_{a_o}'' = 31$

" magnet frame: $\mathbf{B}_m'' = 90,000$; $\mathbf{H}_{m_o}'' = 51$.

Hence, the excitation on open circuit, or the *shunt excitation:*

$at_{g_o} = .313 \times 45,000 \times \frac{1}{4} = 3,520$ ampere-turns;

$at_{a_o}' = 700 \times 2 = 1,400$ "

$at_{a_o}'' = 31 \times 5 = 170$ "

$at_{m_o} = 51 \times 26 = 1,330$ "

Total: $AT = \mathbf{6,420}$ "

The total E. M. F. at normal load, according to formula (**55**), if we assume the armature resistance to be .0125 ohm, is:

$$E = 1.05 \times 125 + 1.25 \times 240 \times .0125 = \mathit{135} \text{ volts.}$$

Inserting this value instead of the no-load voltage into (**21**), the flux required for excitation at normal load is found:

$$\Phi = 5{,}000{,}000 \times \frac{135}{125} = \mathbf{5{,}400{,}000} \text{ lines.}$$

The flux densities and specific magnetizing forces for normal load, consequently, are:

$$\mathbf{B}_g'' = 45{,}000 \times \frac{135}{125} = 48{,}600; \quad \mathbf{H}_g'' = .313 \times 48{,}600;$$

$$\mathbf{B}_a = 120{,}000 \times \frac{135}{125} = 130{,}000; \quad \mathbf{H}_a' = 1{,}100;$$

$$\mathbf{B}_a' = 80{,}000 \times \frac{135}{125} = 86{,}400; \quad \mathbf{H}_a' = 43;$$

$$\mathbf{B}_m' = 90{,}000 \times \frac{135}{125} = 97{,}200; \quad \mathbf{H}_m' = 78;$$

and the magnetizing forces at normal load are obtained as follows:

$$\begin{aligned}
at_g &= .313 \times 48{,}600 \times \tfrac{1}{4} &&= 3{,}800 \text{ ampere-turns.}\\
at_a &= 1100 \times 2 &&= 2{,}200 \quad \text{"}\\
at_a'' &= 43 \times 5 &&= 240 \quad \text{"}\\
at_m &= 78 \times 26 &&= 2{,}030 \quad \text{"}\\
at_r &\text{ (from Par. } \mathbf{69}) &&= 630 \quad \text{"}\\
\text{Total:} & & AT &= \mathbf{8{,}900} \quad \text{"}
\end{aligned}$$

As shown in Par. **74**, the series winding must supply the difference between the ampere-turns on normal load and on open circuit, or, by (**53**):

$$AT_{se} = 8{,}900 - 6{,}420 = \mathbf{2{,}480} \text{ ampere-turns.}$$

The series winding is, therefore, calculated as follows:

The four series coils being connected in parallel, the current in each coil is

$$240 \div 4 = 60 \text{ amperes,}$$

while the magnetizing force per magnet is

$$2{,}480 \div 2 = 1{,}240 \text{ ampere-turns;}$$

hence, the number of series turns per coil:

$$T_{se} = \frac{1240}{60} = \mathbf{21.}$$

The size of the series field conductor is:

$$d_m^2 = 60 \times 1{,}000 = \mathbf{60{,}000} \text{ circular mils,}$$

or **3** *No.* **7** wires.

The series winding is usually wound upon the core first. Assuming it to occupy a height of ½ inch, the mean length of one turn is:

$$l_t' = (6\tfrac{5}{8} + \tfrac{1}{2}) \times \pi = 22.4 \text{ inches, or } 1.87 \text{ feet.}$$

There being on each magnet 3 coils in parallel, each having 21 turns, the joint series resistance (four magnets in parallel) is therefore found:

$$r_{se} = \frac{21 \times 1.87 \times .000497}{3 \times 4} = \mathbf{.00163} \text{ ohm at } 20^\circ \text{ C.,}$$

or

$$.00163 \times 1.12 = \mathbf{.00183} \text{ ohm at } 50^\circ \text{ C.}$$

Hence, the total power loss in the series winding:

$$240^2 \times .00183 = \mathbf{105} \text{ watts.}$$

Since the diameter of No. 7 wire is .154 inch, each layer will hold

$$(4 - \tfrac{1}{2}) \div .154 = \mathbf{21} \text{ turns,}$$

and there will be

$$(21 \times 3) \div 21 = \mathbf{3} \text{ layers,}$$

occupying a height of

$$3 \times .154 = \tfrac{1}{2} \text{ inch.}$$

This, according to Table **27**, leaves a winding depth of about $1\frac{3}{4}$ inches for the shunt coil which is wound over the series coil. The total weight of the series winding is:

$$wt_{se} = 21 \times 3 \times 4 \times 1.87 \times .0645 = \mathbf{30.5} \text{ pounds.}$$

The size of the shunt wire is:

$$d_m{}^2 = \frac{6{,}420 \times 28.6}{125 - 15} = \mathbf{1{,}670} \text{ circular mils, or No. } \mathbf{18} \text{ wire.}$$

In Par. **79**, the total cooling surface of two magnets of this machine is found 355 square inches; the power loss in the series winding is $\frac{1}{2} \times 105 = 52$ watts per magnetic circuit; hence, the shunt current:

$$C_{sh} = \frac{(\frac{35}{75} \times 355) - 52}{110} = \mathbf{1.04} \text{ amperes.}$$

Number of shunt turns:

$$T_{sh} = \frac{6{,}420}{1.04} = \mathbf{6{,}170} \text{ per circuit, or } \mathbf{3{,}085} \text{ turns per core.}$$

The diameter of No. 18 wire is .045 inch; hence, there are

$$3\frac{1}{2} \div .045 = \mathbf{77} \text{ turns}$$

in each layer, and the number of layers becomes

$$3{,}085 \div 77 = \mathbf{40},$$

for which the winding depth is

$$40 \times .045 = 2 \text{ inches.}$$

The mean length of the shunt turn, therefore, is:

$$l_t'' = (6\frac{5}{8} + 2 \times \frac{1}{2} + 2) \times \pi = 30.24 \text{ inches, or } 2.54 \text{ feet.}$$

Resistance of shunt winding:

$$r_{sh} = 77 \times 40 \times 2.54 \times .00638 = \mathbf{50} \text{ ohms, at } 20^\circ \text{ C.,}$$

or $$r_{sh}' = 50 \times 1.12 = \mathbf{56} \text{ ohms, at } 50^\circ \text{ C.}$$

Actual shunt current:

$$C_{sh} = \frac{6{,}420}{2 \times 77 \times 40} = \mathbf{1.04} \text{ amperes.}$$

Total resistance of shunt circuit:

$$r = \frac{125}{2 \times 1.04} = \mathbf{60} \text{ ohms.}$$

Resistance of field regulator:

$$60 - 56 = \mathbf{4} \text{ ohms.}$$

Weight of shunt winding:

$$wt_{sh} = 4 \times 77 \times 40 \times 2.54 \times .0051 = \mathbf{159.5} \text{ lbs.}$$

Total weight of winding:

$$wt_m = 159\tfrac{1}{2} + 30\tfrac{1}{2} = \mathbf{190} \text{ lbs.}$$

CALCULATION OF EFFICIENCIES.

81. Electrical Efficiency.—The *electrical efficiency*, or. as it is sometimes called, the *economic coefficient* of a dynamo, is the ratio of its useful power to the total electrical power in its armature. The total electrical power is the sum of the useful power and of the power losses due to the armature and field resistances; hence the electrical efficiency of a *generator:*

$$El.\ Eff. = \frac{W}{W'} = \frac{W}{W + w_a + w_m}, \qquad \text{(56)}$$

and that of a *motor:*

$$El.\ Eff. = \frac{W'}{W} = \frac{W - (w_a + w_m)}{W}, \qquad \text{(57)}$$

where W = electrical power at terminals of machine;
W' = electrical power active in armature;
w_a = power absorbed by armature winding;
w_m = power used for field excitation.

In the case of a *generator*, W is the *output* available at the brushes, while in a *motor* it is the total power delivered to the terminals, that is, the *intake* of the motor.

82. Formulas for Electrical Efficiency.—Inserting into (**56**) and (**57**) the expressions for W, w_a, and w_m in terms of E. M. F., current strength, and resistance, the following formulas for the electrical efficiency are obtained:

Series-wound generator:

$$El.\ Eff. = \frac{EC}{EC + C^2(r_a' + r_{se}')};\ldots\ldots\ldots\ldots(58)$$

Shunt-wound generator:

$$El.\ Eff. = \frac{EC}{EC + C_a^2 r_a + C_{sh}^2 r_{sh}''};\ldots\ldots\ldots\ldots(59)$$

Compound-wound generator:

$$El.\ Eff. = \frac{EC}{EC + C_a^2(r_a' + r_{se}') + C_{sh}^2 r_{sh}''};\ldots(60)$$

Series-wound motor:

$$El.\ Eff. = \frac{EC - C^2(r_a' + r_{se}')}{EC};\ldots\ldots\ldots\ldots(61)$$

Shunt wound motor:

$$El.\ Eff. = \frac{EC - (C_a^2 r_a' + C_{sh}^2 r_{sh}'')}{EC};\ldots\ldots\ldots(62)$$

Compound-wound motor:

$$El.\ Eff. = \frac{EC - [C_a^2(r_a' + r_{se}') + C_{sh}^2 r_{sh}'']}{EC}\ldots(63)$$

The symbols used in the above formulas (**58**) to (**63**) represent E. M. F., current strengths, and resistances, as follows:

E = terminal voltage of generator, or supply voltage of motor;

C = current output of generator at brushes, or current intake of motor at brushes;

C_{sh} = current flowing in shunt circuit;

C_a = armature current; for a *generator*, $C_a = C + C_{sh}$; for a *motor*, $C_a = C - C_{sh}$;

r_a' = armature resistance, warm;
r_{se}' = series field resistance, warm;
r_{sh}' = resistance of shunt circuit, including field regulator.

The electrical efficiency of modern dynamos is very high, ranging from *.8*, or *80* per cent., for small machines, to as high as *.995*, or *99½* per cent., for very large generators. Since the electrical efficiency does not include waste by hysteresis, eddy currents, and friction, but is dependent upon the power losses due to heating by the current only, it may be adjusted to any desired value by properly proportioning the resistances of the machine.

83. Examples of Calculating Electrical Efficiency.—The following examples show the application of formulas (**58**) to (**63**):

(**1**) *What is the electrical efficiency of a series-wound generator, producing* **2,500** *volts and* **10** *amperes, if its warm armature resistance is* **9** *ohms and its magnet resistance is* **11** *ohms?*

Solution.—By formula (**58**) we have in this case:

$$El. Eff. = \frac{2500 \times 10}{(2500 \times 10) + [10^2 \times (9 + 11)]} = \frac{25,000}{25,000 + 2000}$$
$$= \frac{25,000}{27,000} = \mathbf{.925}, \text{ or } \mathbf{92\tfrac{1}{2}\%}.$$

(**2**) *Find the electrical efficiency of a shunt-wound* **3** *K. W.* **125**-*volt generator, knowing its armature resistance (warm) to be* **.32** *ohm, and its shunt resistance, including field regulator,* **125** *ohms.*

Solution.—The current output of this machine is $\frac{3000}{125}$ = *24* amperes, and the shunt current is found, by Ohm's Law, $\frac{125}{125}$ = *1* ampere. Hence the total current flowing in the armature, being the sum of current output and shunt current, is 24 + 1 = *25* amperes. By (**59**) we therefore obtain:

$$\text{El. Eff.} = \frac{3000}{3000+(25^2\times.32)+(1^2\times125)} = \frac{3000}{3000+200+125}$$

$$= \frac{3000}{3325} = \mathbf{.902}, \text{ or } \mathbf{90.2\%}.$$

(**3**) *A compound-wound* **50** *K. W. generator gives a terminal E. M. F. of* **500** *volts. Its armature resistance (warm) is* **.12** *ohm; its series field resistance is* **.04** *ohm; and its shunt resistance is* **270** *ohms. Compute its electrical efficiency.*

Solution.—The current output is $\frac{50,000}{500} = 100$ amperes; the shunt current is $\frac{500}{270} = 1.85$ amperes. Hence by (**60**):

$$\text{El. Eff.} = \frac{50,000}{50,000+[101.85^2\times(.12+.04)]+(1.85^2\times270)}$$

$$= \frac{50,000}{50,000+1660+925} = \frac{50,000}{52,585} = \mathbf{.95}, \text{ or } \mathbf{95\%}.$$

(**4**) *Find the electrical efficiency of a series motor which takes a current of* **100** *amperes when supplied at* **220** *volts, if its armature has a resistance of* **.11** *ohm, and its field a resistance of* **.015** *ohm.*

Solution.—By (**61**):

$$\text{El. Eff.} = \frac{(220\times100)-[100^2\times(.11+.015)]}{220\times100} = \frac{22,000-1250}{22,000}$$

$$= \frac{20,750}{22,000} = \mathbf{.9425}, \text{ or } \mathbf{94\tfrac{1}{4}\%}.$$

(**5**) *What is the electrical efficiency of the machine considered under* (**2**), *if it is run as a motor from a* **125**-*volt circuit, being supplied with* **26** *amperes?*

Solution.—By (**62**):

$$\text{El. Eff.} = \frac{(125\times26)-[(25^2\times.32)+(1^2\times125)]}{125\times26} = \frac{3250-325}{3250}$$

$$= \frac{2925}{3250} = \mathbf{.90}, \text{ or } \mathbf{90\%}.$$

(6) ***A certain* 75 *H. P. compound-wound motor takes* 140 *amperes on a* 440*-volt circuit; its armature resistance is* .06 *ohm; series field resistance,* .007 *ohm; shunt resistance,* 293 *ohms; compute its electrical efficiency.***

Solution.—The current employed for shunt excitation in this case is $\frac{440}{293} = 1.5$ amperes; hence the current flowing in the armature, 140 − 1.5 = *138.5* amperes, and therefore by formula (**63**):

$$El.\ Eff. = \frac{(440 \times 140) - [(138.5^2 \times .067) + (1.5^2 \times 293)]}{440 \times 140}$$

$$= \frac{61{,}610 - 1945}{61{,}610} = \frac{59{,}665}{61{,}610} = \mathbf{.968},\ \text{or}\ \mathbf{96.8\%}.$$

84. Commercial Efficiency.—By the *commercial efficiency*, or *net efficiency*, of a dynamo-electric machine is meant the ratio of its output to its intake. The *intake of a generator* is the mechanical power required to drive it, and is the sum of the total electrical power generated in the armature and of the power losses due to hysteresis, eddy currents, and friction; the *intake of a motor* is the electrical power delivered to its terminals. The *output of a generator* is the electrical power available at its terminals; the *output of a motor* is the mechanical power available at its shaft, and consists in the useful power of the armature diminished by the losses due to hysteresis, eddy currents, and friction.

The commercial efficiency of a *generator*, therefore, is:

$$Com.\ Eff. = \frac{W}{W''} = \frac{W}{W'+w_o} = \frac{W}{W'+w_h+w_e+w_f}$$

$$= \frac{W}{W + w_a + w_m + w_h + w_e + w_f}, \ldots\ldots \mathbf{(64)}$$

and that of *motor:*

$$Com.\ Eff. = \frac{W''}{W} = \frac{W'-w_o}{W} = \frac{W-(w_h+w_e+w_f)}{W}$$

$$= \frac{W - (w_a + w_m + w_h + w_e + w_f)}{W}; \ldots (65)$$

in which W = electrical power at terminals; that is, output of generator, or intake of motor;

W' = electrical power active in armature;

W'' = mechanical power at dynamo shaft; that is, driving power of generator, or mechanical output of motor, respectively;

w_a = power absorbed by armature winding;

w_m = power used for field excitation;

w_h = power consumed by hysteresis;

w_e = power consumed by eddy currents;

w_f = power loss due to air resistance, brush friction, journal friction, etc.;

w_o = power required to run machine at normal speed on open circuit;

$w_o = w_h + w_e + w_f$.

85. Formulas for Commercial Efficiency.—Substituting in the above formulas (**64**) and (**65**) the values of W, w_a, and w_m, the following formulas are obtained, in which the symbols employed have the same meaning as in formulas (**58**) to (**63**):

Series-wound generator:

$$Com.\ Eff. = \frac{E}{EC + C^2(r_a' + r_{se}') + w_h + w_e + w_f}; \ldots\ldots (66)$$

Shunt-wound generator:

$$Com.\ Eff. = \frac{EC}{EC + C_a^2 r_a' + C_{sh}^2 r_{sh}'' + w_h + w_e + w_f}; \ldots (67)$$

Compound-wound generator:

$$Com.\ Eff. = \frac{EC}{EC + C_a^2(r_a' + r_{se}') + C_{sh}^2 r_{sh}'' + w_h + w_e + w_f}; \ldots (68)$$

Series-wound motor:

$$Com.\ Eff. = \frac{EC - [C^2(r_a' + r_{se}') + w_h + w_e + w_f]}{EC}; \ldots\ldots (69)$$

Shunt-wound motor:

$$Com.\ Eff. = \frac{EC - (C_a^2 r_a' + C_{sh}^2 r_{sh}'' + w_h + w_e + w_f)}{EC}; \ldots (70)$$

Compound-wound motor:

$$Com.\ Eff. = \frac{EC - [C_a^2(r_a' + r_{se}') + C_{sh}^2 r_{sh}'' + w_h + w_e + w_f]}{EC} \ldots (71)$$

86. Friction Losses in Dynamo-Electric Machines.

—In the above formulas all the quantities are known from the previous calculation of the machine, except the amount of power lost by friction; the latter will not be accurately known until the machine is actually built, and must, therefore, here be assumed. Average values of w_f for various sizes of machines, as gathered from experience, are given in Table 29.

TABLE 29.

AVERAGE FRICTION LOSSES IN DYNAMO-ELECTRIC MACHINES.

Capacity of Dynamo, in Kilowatts.	Average Friction Loss in Watts. w_f	Friction Loss in per cent. of Output.
.1	20	20%
.25	40	16
.5	60	12
1.	100	10
5.	400	8
10.	700	7
25.	1500	6
50.	2500	5
100.	4000	4
500.	17500	3½
1000.	30000	3
5000.	125000	2½

To obtain the approximate power lost by friction for any intermediate size not given in Table **29**, take the nearest, or the proportionate, percentage from the last column, and multiply the number so obtained by *10* times the output of the machine in kilowatts. The result will be the required power loss, in watts. Thus, for a *15* K. W. machine, the percentage of power loss by friction is about $6\frac{2}{3}$ per cent.; hence the approximate amount of the power loss:

$$6\tfrac{2}{3} \times 15 \times 10 = 1000 \text{ watts.}$$

If the *nearest* percentage given in the table is taken, the power loss for a 15 K. W. machine is found

$$7 \times 15 \times 10 = 1050 \text{ watts.}$$

87. Examples of Calculating Commercial Efficiency.—To show the use of formulas (**66**) to (**71**), and of Table **29**, let us determine the *commercial efficiencies* of the machines considered in Par. **83**.

(**1**) *The* **2500**-*volt* **10**-*ampere series generator referred to in Example* (**1**) *of Par.* **83** *has a hysteresis loss of* **400** *watts, and an eddy current loss of* **100** *watts; determine its commercial efficiency.*

Solution.—According to Table **29**, the friction loss of a 25 K. W. machine is about *1500* watts; therefore, by formula (**66**):

$$Com.\ Eff. = \frac{25{,}000}{25{,}000 + 2000 + 400 + 100 + 1500} = \frac{25{,}000}{29{,}000} = .8625, \text{ or } 86\tfrac{1}{4}\%.$$

(**2**) *Find the commercial efficiency of the* **3** *K. W. shunt-wound generator of Example* (**2**), *Par.* **83**, *if its hysteresis loss is* **25** *watts and its eddy current loss* **10** *watts.*

Solution.—From Table **29** it is found that the percentage of friction loss for a 3 K. W. machine is about 9%, hence the approximate friction loss is obtained as 9 × 3 × 10 = *270* watts. Formula (**67**), therefore, gives:

$$Com.\ Eff. = \frac{3000}{3000+200+125+25+10+270} = \frac{3000}{3630}$$
$$= \mathbf{.826}, \text{ or } \mathbf{82.6\%}.$$

(**3**) *The hysteresis loss of the* **50** *K. W. compound-wound generator given in Example* (**3**), *Par.* **83,** *is* **350** *watts, its eddy current loss* **65** *watts; what is its commercial efficiency?*

Solution.—Table **29** gives w_f = 2500 watts; by means of formula (**68**) we therefore obtain:

$$Com.\ Eff. = \frac{50{,}000}{50{,}000+1660+925+350+65+2500}$$
$$= \frac{50{,}000}{55{,}500} = \mathbf{.90}, \text{ or } \mathbf{90\%}.$$

(**4**) *What is the commercial efficiency of the* **220**-*volt series motor of Example* (**4**), *Par.* **83,** *its power loss by hysteresis being* **200** *watts, and its eddy current loss* **50** *watts?*

Solution.—The current taken by this motor is given as 100 amperes, hence its capacity is 220 × 100 = 22,000 watts, or 22 K. W., for which Table **29** gives a friction loss of approximately *6%*. Therefore, w_f = 6 × 22 × 10 = *1320* watts, and by (**69**):

$$Com.\ Eff. = \frac{22{,}000 - (1250 + 200 + 50 + 1320)}{22{,}000}$$
$$= \frac{19{,}180}{22{,}000} = \mathbf{.872}, \text{ or } \mathbf{87.2\%}.$$

(**5**) *Determine the commercial efficiency of the shunt-wound motor given in Examples* (**2**) *and* (**5**) *of Par.* **83,** *if its iron losses are the same as given above for the* **3** *K. W. generator.*

Solution.—By (**70**):

$$Com.\ Eff. = \frac{3250 - (325 + 35 + 270)}{3250} = \frac{2620}{3250}$$
$$= \mathbf{.806}, \text{ or } \mathbf{80.6\%}.$$

(6) ***What is the commercial efficiency of the* 75 *H.P. compound motor considered in Example* (6) *of Par.* 83, *if its hysteresis and eddy current losses aggregate* 1200 *watts?***

Solution.—The capacity of this motor is about *60* K. W., hence the friction loss, by Table **29**, is about $w_f = 5 \times 60 \times 10 = 3000$ watts, and by (**71**):

$$Com.\ Eff. = \frac{61{,}610 - (1945 + 1200 + 3000)}{61{,}610} = \frac{55\ 465}{61{,}610}$$
$$= .90, \text{ or } 90\%.$$

88. Magnitude of Commercial Efficiency.—The commercial efficiency of well-designed machines ranges from *.7*, or *70* per cent., for small dynamos, to *.96*, or *96* per cent., for large ones. The commercial efficiency of a dynamo is always smaller than its electrical efficiency, since the former, besides the electrical power dissipation, includes all mechanical and magnetic power losses, such as are due to journal friction, to hysteresis, to eddy currents, and to magnetic leakage. The commercial efficiency, therefore, depends upon the amount of the electrical efficiency, upon the shape of the armature, upon the design, workmanship, and alignment of the bearings, upon the pressure of the brushes, upon the quality of the iron employed in armature and field magnets, and upon the degree of lamination of the armature core; while the electrical efficiency is a function of the electrical resistances only. The mechanical and magnetic losses vary very nearly proportionally to the speed; the no load power consumption for any given speed, consequently, is approximately equal to the open-circuit loss at normal speed multiplied by the ratio of the given to the normal speed.

89. Efficiency of Belt-Driven Machines.—In the case of *belt-driving*, the mechanical power at the dynamo shaft, in foot-pounds per second, can also be expressed by the product of the belt-speed, in feet per second, and of the effective driving power of the belt, in pounds; or, converted into watts:

$$W'' = \frac{746}{550} \times \frac{v_b'}{60} \times (F_b - f_b) = 1.3564 \times v_b'' \times (F_b - f_b), \quad \ldots\ldots(72)$$

where 746 = number of watts equal to 1 horse-power;
550 = number of foot-pounds per second equal to 1 horse-power;
v_b' = belt velocity, in feet per minute;
v_b'' = belt velocity, in feet per second;
F_b = tension on tight side of belt, in pounds;
f_b = tension on slack side of belt, in pounds.

The commercial efficiency of a *generator*, therefore, may be expressed by:

$$Com.\ Eff. = \frac{W}{W''} = \frac{EC}{1.3564 \times v_b'' \times (F_b - f_b)}, \ldots(73)$$

and the commercial efficiency of a *motor*, by:

$$Com.\ Eff. = \frac{W''}{W} = \frac{1.3564 \times v_b'' \times (F_b - f_b)}{EC} \ldots(74)$$

90. Example of Belt-Driven Machine.—*Compute the commercial efficiency of a* **3** *K. W. belt-driven machine, if its speed is* **1800** *revolutions per minute, its pulley diameter* **6¼** *inches, and if the tension on the tight side of its belt is found to be* **82** *pounds and that on the slack side* **30** *pounds.*

Solution.—The belt velocity in this case is $\frac{6\frac{1}{4} \times \pi}{12} \times 1800$ = *3060* feet per minute, or *51* feet per second. Consequently, by (**73**):

$$Com.\ Eff. = \frac{3000}{1.3564 \times 51 \times (82 - 30)} = \frac{3000}{3600}$$
$$= \mathbf{.833}, \text{ or } \mathbf{83.3\%}.$$

91. Losses in Dynamo Belting.—Since in a direct-driven generator the commercial efficiency is the ratio of the mechanical power available at the engine shaft to the electrical energy at the machine terminals, for comparisons between direct and belt-driven dynamos, the loss in belting should also be included in the formula for the commercial efficiency of the belt-driven generator. The following Table **30** contains averages of these losses for various arrangements of belts:

TABLE 30.
LOSSES IN DYNAMO BELTING.

Arrangement of Belts.	Loss in Belting in per cent. of Power Transmitted.
Horizontal Belt....	5 to 10 per cent.
Vertical Belt......................	6 " 12 "
Countershaft and Horizontal Belt..	10 " 15 "
Countershaft and Vertical Belt	12 " 20 "
Main and Countershaft with Belts..	20 " 30 "

92. Gross Efficiency.—The *gross efficiency,* or the *efficiency of conversion*, in a *generator* is the ratio between the total electrical power generated and the gross mechanical power delivered to the shaft; and in a *motor* it is the ratio of the mechanical output to the total electrical power in the armature.

The gross efficiency is, therefore, the quotient of the commercial and electrical efficiencies, or

$$Gr.\ Eff. = \frac{Com.\ Eff.}{El.\ Eff};\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(75)$$

and consequently varies between $\frac{.7}{.85} = .825$, or $82\frac{1}{2}$ per cent., for small dynamos, and $\frac{.95}{.996} = .965$, or $96\frac{1}{2}$ per cent., for large machines.

93. Example of Gross Efficiency.—*Find the gross efficiency of the* **50** *K. W. compound-wound generator of Example* (**3**), *Pars.* **83** *and* **87**.

Solution.—The electrical efficiency of this generator was found to be *.95*, and its commercial efficiency *.872*; therefore by (**75**):

$$Gr.\ Eff. = \frac{.872}{.95} = \mathbf{.917}, \text{ or } \mathbf{91.7\%}.$$

94. Weight-Efficiency.—The *weight-efficiency* of a dynamo, that is, the output per unit weight, is obtained by dividing the output, in watts, by the weight, in pounds. The numerical value of this ratio shows at a glance whether or not the machine is designed economically, since the weight efficiency indicates how the cost of the prospective machine is going to compare with that of existing dynamos.

The weight-efficiency of modern machines ranges between *2* and *20* watts per pound, according to their speed and size. For *low-speed* dynamos, the limits are from *2* to *10* watts per pound, the former figure referring to very small machines (less than ½ K. W. capacity), and the latter to very large ones (2,000 K. W. and over). In *medium-speed* machines the weight-efficiency varies from *3* to *15* watts per pound, according to the size; and high-speed dynamos have weight-efficiencies from *5* to *20* watts per pound.

To determine the total weight of the machine, compute the weights of the magnet frame, armature, and windings from the dimensions; estimate the weights of the shaft, the bearings, and the bedplate or supporting brackets; and, according to the size and current output of the machine, allow from *5* to *25* per cent. of the total weight so found, for accessory parts, such as commutator, pulley, brushes, brush-rocker, switches, connectors, cables, etc. A small allowance for accessory parts, from *5* to *10* per cent., is to be made in the case of large machines of high voltage in which all the current-carrying parts are comparatively small; and a large allowance, from *15* to *25* per cent., in the case of small, low-voltage machines having comparatively massive current-conveying parts.

The weight of the shaft, bearings, and bed (or supporting brackets) depends upon the type and arrangement of the machine, and varies so widely for different designs of machines that no definite rule for estimating its amount can be given.

To compute the weights of the various parts, multiply their solid contents, in cubic inches, by *.28*, in case of *wrought iron* or *cast steel;* by *.26*, in case of *cast iron;* by *.32*, for *copper;* and by *.30*, for *brass.*

95. Example of Determining Weight-Efficiency.—

Find the weight-efficiency of the toothed-armature shunt-wound four-pole dynamo shown in Fig. 26, page 77.

Solution.—The weights of the various parts of this dynamo are as follows:

Yoke, 27½" external diameter, 22½" internal diameter, 8" breadth:

$$\left[(27\tfrac{1}{2})^2\frac{\pi}{4} - (22\tfrac{1}{2})^2\frac{\pi}{4}\right] \times 8 \times .28 = \ldots\ldots\ldots \quad 440 \text{ lbs.}$$

4 cores, 6⅝" diameter, 4" long:

$$4 \times (6\tfrac{5}{8})^2\frac{\pi}{4} \times 4 \times .28 = \ldots\ldots\ldots\ldots\ldots\ldots \quad 155 \text{ “}$$

Polepieces and *core-seats* on yoke, approximately, 75 “

Magnet winding (see page 111), 148 lbs., or round: 150 “

Armature. Core, 12" external diameter; 6⅞" internal diameter; 10½" long; slots, 1" deep. Provided that the entire height of the slots is occupied by the winding, the dimensions of the wound armature are: External diameter 12", internal diameter 4⅞", length 12½"; and its weight is, practically:

$$\left[(12)^2\frac{\pi}{4} - (4\tfrac{7}{8})^2\frac{\pi}{4}\right] \times 12\tfrac{1}{2} \times .28 = \ldots\ldots\ldots\ldots \quad 330 \text{ “}$$

The total weight of the armature core and winding is here computed approximately by considering the wound armature as a hollow cylinder of iron. A more accurate method is to find the exact weight of the armature core, by deducting from the core, with the slots considered as solid, the weight of the iron in the slots, and adding to it the weight of the winding obtained by Par. **38** and Table **13**.

Bedplate, Journals, and *Shaft* (estimated).......	800 lbs.
Aggregate weight of *principal parts*..........	1950 lbs.
Allowance for *accessory parts* (15% of above figure)....................................	300 "
Total weight of machine........................	*2250 lbs.*

The output of the above dynamo is 125 volts and 240 amperes (see page 88), or *30* kilowatts; hence the weight-efficiency:

$$Wt.\ Eff. = \frac{30{,}000}{2250} = \mathbf{13.3} \text{ watts per pound.}$$

This being a very high weight-efficiency for a dynamo of the given size and speed, it follows that the machine is economically designed, and would, when built, compare favorably, as to lightness and cost, with existing machines.

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QUESTIONS
ON
THE DESIGN OF DIRECT-CURRENT
DYNAMOS AND MOTORS

THE DESIGN OF DIRECT-CURRENT DYNAMOS AND MOTORS.

1. In what form is a problem of generator design usually given?

2. Give the formula for the current strength of a generator if its capacity and voltage are known.

3. State the form in which a problem of motor calculation is usually given.

4. Give the formula for the output of a generator which corresponds to a motor of given horse-power.

5. Express the counter E. M. F. of a motor in terms of the supply voltage.

6. By what formula can the current strength of a motor be found, if its output, its voltage, and its electrical efficiency are given?

7. Find the electrical power equivalent to a motor output of 15 horse-power.

8. What is the average counter E. M. F. of a 2 H. P. motor designed to operate on a 110-volt circuit?

9. Compute the full-load current of a 50 H. P. motor run from a 250-volt circuit.

10. Give the average electrical efficiency of a 3 H. P. motor.

11. What is the average commercial efficiency of a 35 H. P motor?

12. State the four principal forms of armatures.

13. Which of the four types of armatures referred to in the preceding question are most used? Give also the scope of the other types.

14. Name the chief advantage of the ring type of armature.

15. State the advantage of formed armature coils.

16. What is the principal advantage of the drum type of armature?

17. What is the latest practice in the selection of the type for an armature?

18. What is the object of laminating the armature core?

19. In which direction should the armature core be laminated relative to the direction of the magnetic flux and to the direction of rotation?

20. State the disadvantages of armature cores built of iron wire.

21. How are the core discs arranged in armatures of small and of large sizes?

22. What is the usual thickness of the sheet iron employed for core discs?

23. How are the core laminæ insulated from each other?

24. How does the lamination of the armature core affect its magnetic carrying capacity?

25. What is understood by the effective cross-section of the armature core?

26. Name the advantages of toothed armatures.

27. State the disadvantages of toothed armatures.

28. How should the slots of a toothed armature be proportioned so as to avoid the generation of eddy currents in the pole pieces?

29. Name some expedients employed to reduce the eddy current tendency due to improperly proportioned toothed armatures.

30. What are the objections to perforated armatures?

31. Name the chief points to be considered in determining the size of an armature.

32. Give the formula for the peripheral velocity of an armature.

33. Express the diameter of an armature in terms of its peripheral velocity, v, and its revolving speed, n_1.

34. What are the limits of the peripheral velocity in practical machines?

35. Give the average value of v for high-speed ring machines.

36. What is the average peripheral velocity of medium-speed ring machines?

37. State the average of v for low-speed machines.

38. What is the average circumferential velocity of drum armatures?

39. Give the approximate armature velocity for a high-speed ring machine of 25 K. W. capacity.

40. What peripheral velocity should be chosen for a 400 K. W. low-speed direct-connected machine?

41. State the approximate velocity of a 600 K. W. medium-speed ring armature.

42. Give the approximate peripheral speed of a 25 K. W. drum armature.

43. Name the kinds and sizes of machines for which 3,000 feet per minute is a good value for the peripheral velocity.

44. Define the cooling surface of an armature.

45. What portion of its surface do we consider the cooling area of a drum armature? Why not the entire surface of the core?

46. Give the formula for the cooling surface of a drum armature in terms of its diameter and length.

47. What is the formula for the cooling surface of a drum armature, expressed in terms of its diameter and shape ratio?

48. What area is usually considered the cooling surface of a ring armature?

49. Give the formula for the usual case of the cooling surface of a ring armature, if all its dimensions are given.

50. What formula is used for the cooling surface of a ring armature, if only its diameter is given and its shape ratios are assumed?

51. How much cooling surface is needed to dissipate the heat corresponding to 1 watt of power loss?

52. Give the formula for the cooling surface required for a dynamo having a capacity of W watts.

53. What is the average percentage of power loss in a 75 K. W. machine?

54. Give the usual limits of the actual power loss (in kilowatts) of a 200 K. W. dynamo.

55. From Table **3,** Instruction Book, find the usual limits and the average of the power loss in a 10 K. W. dynamo.

56. Give the formula for the diameter of a drum armature having a cooling surface proportional to its capacity W.

57. State the corresponding formula for a ring armature.

58. What value of s should be used in the formula for drum armatures referred to in Question **56?**

59. Give the value of the specific cooling surface employed in connection with the formula for ring armatures referred to in Question **57**.

60. Give the average ratios **(a)** of length to diameter, and **(b)** of radial thickness to diameter, for a 10-foot ring armature, using Table **4,** Instruction Book.

61. From the answer to the preceding question find the average length and radial thickness of a ring armature having a diameter of 10 feet.

62. State the approximate shape ratios of a ring armature 20 inches in diameter.

63. What is the average shape ratio, m, and the length, L_a, of a drum armature 8 inches in diameter?

64 Give the approximate average length of a drum armature having a diameter of 36 inches.

65. What must be the diameter of a 100 K. W. drum armature designed to run at 450 revolutions per minute, in order to have the proper peripheral velocity as given by Table **2**, Instruction Paper?

66. Compute the smallest diameter which the armature, specified in the preceding question, must have in order that its specific cooling surface be at least $s = .7$ square inch per watt, when assuming a percentage of power loss of $k = .04$ and a shape ratio of $m = 1.25$.

67. A 12 K. W. drum armature is to run at a speed of 1,000 revolutions; find the diameter for which both the circumferential velocity and the cooling surface are nearest to the averages given in Tables **2**, **3**, and **4**, Instruction Paper.

68. Determine the diameter of a 300 K. W. direct-driven ring armature for a speed of 150 revolutions per minute both by peripheral velocity and by cooling surface, using the average values of v, s, k, m, and m' given in the tables.

69. Give the length and radial thickness of the armature considered in the preceding example, and compute its actual cooling surface from the dimensions.

70. Determine in a similar manner the cooling surface of the drum armature of Question **67**.

71. From Table **5**, page 17, Instruction Paper, find the shape ratio m of the $7\frac{1}{2}$ H. P. *Crocker-Wheeler* motor, the length of the armature being the dimension marked J, and the diameter being the dimension designated by Y.

72. Using the data given in Table **5**, compute the peripheral velocity of the 3 H. P. *Crocker Wheeler* motor, the armature diameter Y being expressed in inches.

73. What are the smallest and greatest values of the velocity *v* in the *Edison* bipolar drum machines tabulated on page 18, Instruction Book? State which size machine has the minimum value of *v*, and for which size *v* is a maximum.

74. Give the maximum and minimum values of the shape ratio *m* for *Edison* drum armatures.

75. From Table **7**, Instruction Book, find the average value of the velocity *v* for *Westinghouse* medium-speed drum armatures.

76. Find a similar average for *General Electric* medium-speed ring armatures, from Table **8**.

77. Give the values of the shape ratios *m* and *m'* for No. 1, No. 4, and No. 6 machines of Table **8**, Instruction Book.

78. What are the values of *v* used in the 2 K. W., 50 K. W., and 600 K. W. *Crocker-Wheeler* multipolar generators (Table **9**)?

79. What are the shape ratios *m* of the armatures of the machines named in the preceding question?

80. Compute the peripheral velocities of the *General Electric* low-speed generators given in Table **10**.

81. Find the values of the shape ratios *m* referred to in the preceding question.

82. From dimensions *A*, *C*, and *D*, given in Table **10**, determine the ratios *m'*, of radial thickness of the solid portion of the armature core to the diameter, for *General Electric* low-speed multipolar generators.

83. Compare the two 17.5 K. W. high-speed ring machines given in Table **11**.

84. Make a similar comparison between the two 150 K. W. low-speed machines given in the same table.

85. From the data given in Table **11**, Instruction Book, complete the following table of approximate average speeds of high, medium, and low speed ring dynamos:

TABLE OF AVERAGE RING ARMATURE SPEEDS.

Output, in Kilowatts.	High Speed.	Medium Speed.	Low Speed.
2.5	1600	1100	500
5	1400	1000	400
10			
50			
100			
150			
250			
500	....	....	
1000	....	....	

86. From the figures of Table **12** compile a similar table of average drum armature speeds for .5, 1, 2, 5, 10, 25, 50, 100, and 200 K. W. machines.

87. State the limits between which it is customary to choose the specific cross-section of the armature conductor.

88. What is the specific conductor cross-section usually allowed in armatures for ordinary dynamos?

89. In what class of machines is it expedient to use the lower limit referred to in Question **87**, and in what class of machines is the upper limit of specific cross-section employed?

90. What portion of the total current flows through each armature conductor in a bipolar armature?

91. How is a current in any conductor of a multipolar dynamo related to the total current, (a) when opposite coils of the armature windings are cross-connected at the commutator, (b) when the brushes are connected in parallel, (c) when the coils are connected by a two-circuit winding?

92. A six-pole machine furnishes a total current of 300 amperes; what is the current flowing in each wire, if the winding is cross connected, and if each conductor consists of 2 wires connected in parallel?

93. What must be the gauge of the wire referred to in the preceding question, if a specific area of 800 circular mils per ampere is taken? Use Table **13**, Instruction Book.

94. Given a smooth armature of 9 inches diameter, how many No. 12 B. & S. wires can be wound on it, if the height of the winding space is not to exceed $\frac{1}{2}$ inch, and if one-tenth of the circumference is used for division strips?

95. A smooth ring armature of 30 inches external diameter, 22 inches internal diameter, and 12 inches length, is wound with No. 8 B. & S. wire to a uniform height of $\frac{7}{16}$ inch. Find the number of conductors, the total length of wire and its total resistance, assuming that the entire interior surface is covered by the winding.

96. A toothed armature of 21 inches diameter has 88 slots, each $\frac{3}{8}$ inch wide and $1\frac{7}{16}$ inches deep; how many No. 10 B. & S. wires can be wound on it?

97. Determine the size of conductor required for a 50 K. W. 125-volt bipolar dynamo to be used under ordinary conditions.

98. Find the sectional area required for the armature conductor of a 1200 K. W. 8-pole railway generator (550 volts) for central station use.

99. Compute the gauge of the armature wire for a 30 H. P. bipolar elevator motor to run on a 220-volt circuit.

100. What size wire should be used for a 12 K. W. 4-pole arc-light generator delivering 10 amperes and having a two-circuit winding?

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101. Upon what does the number of conductors depend which can be placed upon an armature of given diameter?

102. Give the average winding height of a 6-inch smooth drum armature.

103. What is the average height to which a 50-inch smooth ring armature is usually wound?

104. Give the average depth of slot of a 20-inch toothed armature.

105. Give a simple formula expressing the cross-section of the winding space on a smooth-core armature.

106. What average percentage of the total winding space is occupied by insulation, etc., in an ordinary smooth-core armature machine?

107. State formula giving the available inductor space on a smooth-core armature.

108. Give formula for total number of conductors on a smooth-core armature, if the diameter of the core, the winding height, and the thickness of the wire are known.

109. State the formula for the approximate total number of conductors on a toothed armature, if the armature diameter, the winding height, and the size of wire are given.

110. What is the usual practice with reference to the number of commutator segments for dynamos of various voltages?

111. How is the final number of wires per layer in a smooth-core armature found?

112. How is the arrangement of armature inductors adjusted, when the final number of wires per layer referred to in the preceding question is found about half-way between two whole numbers?

113. How can a given winding space be utilized to the best advantage, electrically?

114. Give average number of slots for toothed armatures of various diameters.

115. By means of formula **16,** find the approximate number of No. 12 B. & S. wires that can be wound upon a smooth drum armature 4½ inches in diameter, and verify result by use of Table **13,** Instruction Book.

116. How many No. 9 B. & S. wires can be placed on a smooth ring armature having an external diameter of 30 inches? Use both formula (**16**) and Table **13.**

117. Determine the number of No. 5 B. & S. wires which may be put on a 60-inch smooth ring armature.

118. Compute the approximate number of No. 7 B. & S. wires on a 32 inch toothed armature, using formula (**17**), Instruction Book.

119. Check the result obtained in answer to the preceding question by means of the data given in Table **13.**

120. Check the answer to Question **118** by means of Tables **14** and **15.**

121. State the fundamental relation between the rate of cutting magnetic lines and the voltage generated.

122. What is the voltage generated per foot of armature inductor under unit conditions?

123. What are termed the idle conductors on an armature, and what percentage does their number usually bear to the total number of conductors?

124. Give the formula for the total E. M. F. generated in an armature.

125. By transformation of the E. M. F. formula referred to in the preceding question, give the expression for the length of armature inductor required to produce a certain voltage.

126. Upon what does the gap induction in a dynamo depend?

127. How can Table **16** be used for machines in which a strong field is desired?

128. How is Table **16** used in case of electroplating machines, battery motors, and incandescent generators?

129. From Table **16** find the approximate gap density for a 25 K. W. smooth armature bipolar dynamo having cast iron polepieces.

130. What field density should be chosen for the machine referred to in the preceding question, if it had a toothed armature and cast steel pole shoes?

131. Give the average field induction which should be taken for a 50 K. W. multipolar dynamo with smooth armature and wrought iron polepieces, if a strong magnetic field is required.

132. What gap density is to be used for a 10,000-light multipolar incandescent generator having a toothed armature and steel polepieces?

133. Give the average field density employed for the machine referred to in the preceding question, in case of a smooth-core armature and strong field.

134. Express the length of the armature core in terms of the number of inductors and of their active length.

135. If an armature has N inductors and n_p bifurcations, what is the number of inductors effective in generating the total voltage?

136. Give the formula for the armature flux in terms of the electrical data of the machine.

137. Express the armature flux in terms of the field density and of the dimensions of the armature.

138. The total armature flux of a 6-pole dynamo being 9,000,000 lines, what is the flux per pole?

139. Find the armature flux of a bipolar 60 K. W. 130-volt generator, having 100 armature inductors and running at a speed of 700 revs. per min.

140. By the use of formula (**22**), compute the gap induction of the machine given in the preceding example, provided that its armature has a diameter of 15 inches and a length of 24 inches.

141. A 300 K. W. 4-pole railway generator gives 550 volts at 4 0 revs. per min.; its frame is of cast iron, and it has a toothed ring armature, 44 inches in diameter and 27 inches long, which is wound with 360 conductors arranged in 4 circuits. Find the armature flux by formula (**21**) and check the result by formula (**22**), using Table **16.**

142. Give formula for radial depth of armature core.

143. What is the average practical flux density in the armature core, (**a**) for ordinary bipolar machines, (**b**) for ordinary multipolar dynamos, (**c**) for arc lighting machines, (**d**) for low-voltage machines, and (**e**) for alternators?

144. The armature of a bipolar incandescent dynamo is 12 inches long; the armature flux is 6,000,000 lines. How deep should the core be made?

145. Compute the proper breadth of cross-section for the armature of a 4-pole arc lighting machine from the following data: Diameter, 23 inches; length, 9 inches; gap induction, 15,000 lines per square inch.

146. Show how to find the radial depth in the preceding example, if the length of the armature is not given.

147. Find the radial depth of the armature core of an 8-pole railway generator, having 2,400 armature conductors, if at 175 revs. per min. its voltage is 550, and if the length of the armature is 13½ inches.

148. What should be the internal diameter of a 6-pole ring armature whose external diameter is 17 inches and whose length is 5 inches, if the total armature flux is 2,700,000 lines?

149. Give the formula for the total length of conductor on a drum armature.

150. What are the usual limits of the numerical value of the factor *k* in the formula referred to in the preceding question?

151. Compute the average total length of wire on a smooth drum armature, 8 inches in diameter and 15 inches long, if its winding consists of 66 coils, each having 2 turns.

152. What is the total length of conductor of a toothed drum armature, 8 inches in diameter, 14 inches long, having 36 slots, each holding 8 wires, the depth of the slots being 1 inch?

153. Define a spirally wound armature.

154. State the formula for the total length of wire on a spirally wound ring armature.

155. A spirally wound smooth-core armature has an external core diameter of 18 inches, and an internal core diameter of 11 inches, and a length of 15 inches; it contains 560 conductors occupying an average height of ½ inch; what is the average total length of wire?

156. Find the approximate total length of wire on a 27-inch armature, 12 inches long, which is wound with 144 formed coils, each consisting of 4 turns and spanning one eighth of the circumference.

157. A 14-pole toothed armature is wound with formed coils. Its diameter is 7 feet; its length, 17½ inches; it has

192 slots, 6 conductors per slot. Compute the approximate total length of wire.

158. If a wire having a resistance of 16 ohms is divided into 8 equal parts, what is the joint resistance of the 8 pieces of wire when connected in parallel?

159. Express the armature resistance in terms of the total resistance of the armature wire and of the number of bifurcations.

160. Give the formula for computing the armature resistance from the total length of wire on the armature.

161. What is meant by the resistivity of a wire?

162. How is the resistivity at a temperature higher than 20° C. found?

163. What is the rule for computing the resistivity of a warm wire, when the temperature is given in Fahrenheit degrees?

164. By what factor must the resistivity at 68° F. be multiplied to obtain the resistivity at 160° F.?

165. What is the resistivity of No. 9 B. & S. wire at 50° C.?

166. Find the resistance at 80° C. of the armature given in Example **151,** if each conductor consists of 4 No. 13 B. & S. wires.

167. What will be the resistance in the previous case, if the armature, in order to produce double the voltage and one-half the current output, is connected up so that each conductor consists of only 2 No. 13 wires?

168. Give the resistance of the armature referred to in Question **166** for the case that it is wound in 4 parallel circuits suitable for a 4-pole field.

169. Compute the resistance at 76° C. of a bipolar drum armature 23¾ inches in diameter, 26⅛ inches long, and wound with 40 coils, each coil consisting of 1 turn of 20 No. 7 B. & S. wires.

170. A 6 pole ring armature having an external diameter of 42 inches, an internal diameter of 34 inches, and a length of 11 inches. is wound spirally with 600 turns of 2 No. 6 B. & S. wires, in two layers. Find its resistance at 60° C.

171. What would be the resistance of the armature in the preceding example, if it were wound with 1,200 turns of 1 No. 6 B. & S. wire so as to give double its previous voltage in a 4-pole field?

172. How can the armature design be checked with reference to the heating limit?

173. If the temperature increase of the armature is found excessive, how must the armature be re-designed?

174. Give formula for computing the power loss in the armature winding.

175. How can the exact amount of the shunt current in a completed machine be computed?

176. Tabulate the average factors by which the external current of shunt and compound wound generators and motors of various capacities must be multiplied, in order to obtain the current flowing in the armature.

177. What is the formula for the power loss by hysteresis?

178. What does the hysteresis factor express?

179. How can the hysteresis factor for any given flux density be calculated?

180. What is the value of the hysteresis factor for a flux density of 77,500 lines per square inch?

181. Find the hysteresis factor for a density of 142,000 lines per square inch.

182. How is the frequency of a dynamo obtained?

183. Give formula for the mass of the armature core.

184. By what formula is the power loss by eddy currents calculated?

185. What is the eddy current factor, and upon what does its magnitude depend?

186. Give the eddy current factor for sheet iron, 20 mils thick, at a flux density of 94,000 lines per square inch.

187. What is the eddy current factor for .012-inch sheet iron at 85,000 lines per square inch?

188. Compute the eddy current factor at 88,000 lines for a thickness of lamination of $\frac{1}{32}$ inch.

189. How is the specific power loss in the armature obtained?

190. Tabulate the average temperature increase of drum and ring armatures corresponding to various values of the specific cooling surface.

191. What is the probable average temperature rise of a ring armature, for which the value of the specific cooling surface has been found to be .85?

192. What is meant by the circumferential current density of an armature?

193. Give the formula for the circumferential current density of any armature.

194. Compile the average values of the temperature rise corresponding to various values of the circumferential current density.

195. If the circumferential current density of a high-speed armature has been found to be $c = 335$, what will be the probable average temperature rise?

196. Find the probable temperature increase of a bipolar drum armature of which the following data are known: Output (constant potential), 250 volts, 100 amperes; speed, 1,300 revs. per min.; diameter, $8\frac{3}{4}$ inches; length, $16\frac{1}{2}$ inches; inside diameter of disc, $3\frac{1}{2}$ inches; thickness of sheet iron, .020 inch; winding, 66 coils of 2 turns of No. 6 B. & S. wire; resistance, at 20° C., .06 ohm.

197. Predetermine the approximate average temperature rise of a 100 K. W. ring armature, 66 inches in diameter, which generates 150 volts at 175 revs. per min., and which is wound with 944 conductors connected in 8 circuits.

198. A smooth ring armature, having an external core diameter of 106 inches, an internal diameter of $95\frac{3}{4}$ inches, and a length of 26 inches, generates a current of 800 amperes at 500 volts, when running at a speed of 100 revs. per min.; the sheet iron used for its core disc has a thickness of .020 inch; its winding consists of 1,632 turns of 2 No. 5 B. & S. wires; the field magnet has 12 poles and is compound wound. What temperature increase may be expected under average conditions?

199. A bipolar toothed armature $38\frac{1}{2}$ inches in diameter has 138 slots, $\frac{7}{16}$ inch wide by $1\frac{9}{16}$ inch deep; its length is 10 inches; the radial depth of its solid portion is $6\frac{3}{4}$ inches; its core is built up of .015-inch sheet iron; its winding consists of 46 coils, each coil having 9 turns of 20 No. 12 B. & S. wires; the coils are wound spirally, 60 wires being placed in each slot. When running at 200 revs. per min., the output of this armature is 50 K. W., at 125 volts; to what average final temperature is it expected to heat, if the temperature of the dynamo room is 18° C.?

200. Compute the temperature increase of the armature of a 16-pole compound-wound railway generator from the following data: Output, 2,000 kilowatts, at 540 volts; speed, 70 revs. per min.; external diameter of toothed core, 144 inches; diameter at bottom of slots, $137\frac{3}{4}$ inches; internal diameter of core, 124 inches; length of core, 32 inches; thickness of discs, .018 inch; winding, 2,016 copper bars, $\frac{7}{8}$ inch high by $\frac{1}{4}$ inch wide, arranged in 336 slots, $\frac{11}{16}$ inch wide; resistivity of armature conductor, .0000375 ohm per foot; interconnection of bars effected by end connectors spanning one-sixteenth of circumference.

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201. What is the almost universal modern practice in regard to the adoption of the bipolar and multipolar forms for dynamos of various outputs?

202. Name the advantages of the multipolar form over the bipolar.

203. What are the disadvantages of multipolar machines?

204. Show the saving of material effected in the multipolar construction by comparing a 4-pole frame with a bipolar frame for the same armature.

205. Compare in the same manner as in the preceding question an 8 pole machine with an equivalent one of the bipolar type.

206. If a total flux of 2,400,000 lines is required for an armature of given diameter, what must be the carrying capacity of the armature cross-section for a bipolar, 4-pole, and 8-pole machine, respectively ?

207. Neglecting magnetic leakage, how many lines are carried by each magnet core and by the yoke section of the bipolar, 4 pole, and 8-pole construction in the case considered in the preceding question?

208. Give the formula for the frequency of magnetic reversal in a dynamo-electric machine.

209. What is the frequency of an 8-pole machine when running at 500 revolutions per minute?

210. What are the usual limits of the frequency in direct-current machines?

211. Give the usual average values of the frequencies for low-speed, medium-speed, and high-speed direct-current machines, respectively.

212. Give formula for obtaining the proper speed of a machine corresponding to a given frequency.

213. What must be the speed of a 6-polar dynamo, if a frequency of 15 cycles is desired?

214. Compute the maximum permissible speed of an 8-pole direct-current machine.

215. By transposition of the terms in the frequency formula deduce an expression for the proper number of pole-pairs for a dynamo.

216. From the formula given in answer to the preceding question, find the number of poles for a medium-speed machine running at 400 revolutions per minute.

217. State the proper number of poles for a low-speed 125-revolution machine, by means of Table 23, Instruction Book.

218. Between what limits may the pole number be selected for a 175-revolution high-speed dynamo?

219. For what kind of machines is the bipolar type almost always adopted?

220. In what machines is the 4 pole construction generally used?

221. Name the kinds of machines in which 6 poles or more are employed.

222. What determines the cross-section of a dynamo magnet frame?

223. Give formula for the cross-section of the field frame, and state the meaning of the symbols used.

224. What are the usual limits of the leakage factor for bipolar toothed-armature machines?

225. Between what limits does the leakage factor ordinarily range in bipolar smooth armature machines?

226. Give the usual range of the leakage factor for multipolar ring-type machines having a toothed armature.

227. Between what values does the leakage factor of multipolar smooth-armature dynamos usually vary?

228. State the limits between which the flux density for wrought iron and cast steel should be chosen.

229. What are the best values of the flux density in cast iron?

230. How is the core area of a multipolar machine obtained from the formula referred to in Question **223**?

231. By what number must the total frame area of a multipolar ring-type dynamo be divided to give the cross-section of the yoke?

232. What relation does the yoke-section usually bear to the core-section in multipolar types, if the same material is used for both?

233. Show a multipolar type in which the yoke-section is equal to the core-section.

234. What is the usual relation between core-area and yoke-area in the bipolar types, provided that cores and yoke are of the same material?

235. Sketch a bipolar type in which the yoke-section is only one half the core-section.

236. Tabulate the average values of the leakage factor for the various sizes of the most common types of dynamos, according to Table **24**, Instruction Book.

237. What is the approximate leakage factor of a high-speed 5 K. W. inverted horseshoe type machine, having a smooth armature and cast iron field frame?

238. State the approximate leakage factor of a low-speed 25 K. W. dynamo of the multipolar ring type, having a toothed armature and a cast steel frame.

239. Why is the leakage factor for one and the same magnet frame smaller with a toothed than with a smooth armature?

240. Give reason why a wrought iron or cast steel magnet frame for a given armature results in a machine of smaller leakage than a cast iron frame.

241. If two machines of the same type and construction are designed to have equal output at different speeds, which one will have the greater factor of magnetic leakage, and why?

242. Why is the leakage factor of small machines greater than in large dynamos of the same type?

243. Give rules for the length of the magnet cores in bipolar machines having toothed armatures.

244. State rules similar to those of the preceding question for the length of field cores of bipolar smooth-armature machines.

245. How should the magnet cores of smooth-armature multipolar machines be proportioned ?

246. Give the ratios of length to diameter of magnet cores for large, medium, and small multipolar machines with toothed armatures.

247. Why is it necessary to make the magnet cores longer for smooth-armature machines than for those having toothed armatures?

248. The proper core-section for a bipolar machine having been found to be 50 square inches, what is the average length of each magnet core, if the machine has a smooth armature?

249. What would be the proper length of the magnet cores in the preceding example, if the machine has a toothed armature?

250. Give the average length of the magnet cores for a large 8-pole smooth-armature machine, if it has been found that a total frame area of 1,400 square inches is required.

251. Name the conditions which determine the length of the air gap.

252. Between what limits does the radial depth of the air gap usually range in machines with toothed armatures?

253. State the average radial clearances allowed in very small and in very large smooth-armature machines.

254. What should be the bore of the polepieces for a toothed armature, 41½ inches in diameter?

255. The height occupied by the winding of a smooth-core ring armature, 6 feet in diameter, is ½ inch; find the diameter of the bore of the polepieces, when allowing ⅛ inch for core insulation, binding wires, etc.

256. A smooth drum armature, having a core diameter of 13½ inches, is wound with 4 layers of No. 10 B. & S. wire; the core insulation consists of two layers of mica-cloth, .025 inch thick each, and the binding bands are made up of No. 20 B. & S. phosphor-bronze wire and insulated from the winding by sheet mica, .012 inch thick; give the diameter to which the poles should be bored.

257. Determine the dimensions of the magnet cores for an inverted horseshoe-type dynamo similar to Fig. 25, Instr. Paper, having a smooth drum armature, 7 in. in diameter, 12 inches long, which is wound with 96 turns and is required to generate 125 volts and 120 amperes at 1,500 revolutions per minute. Assume the leakage factor to be 1.30, and take a density in the frame of 80,000 lines per square inch.

258. What would be the dimensions of the cores, if the armature in the preceding example had a toothed instead of a smooth core, the armature dimensions and number of conductors remaining the same?

259. Find the dimensions of the polepieces and yoke of the machine considered in Question **257**, and show a cross-section of the complete magnet frame, making the sketch one-quarter size; insert the dimensions of the various parts; show the inverted horseshoe type.

260. Make a sketch similar to the one asked for in the preceding question, for the machine of Question **258**, having a toothed armature. Draw to the same scale as before and give all the dimensions, assuming the slots to be ¾ inch deep.

261. How is the yoke of a bipolar machine usually dimensioned?

262. Give a formula expressing the height of the yoke of a bipolar machine in terms of the core diameter, provided that the yoke is of the same material as the cores.

263. The diameter, D_m, of the magnet cores and the length, L_a, of the armature being given, express the thickness of the middle section of the polepieces of a bipolar dynamo, supposing the polepieces to be made of the same material as the cores.

264. What effect has slotting of the core upon the dimensions of a small ring armature?

265. Compute the diameter and length of cast steel magnet cores for a 6 pole machine having a smooth armature;

the flux required is 20,000,000 lines, and the factor of leakage 1.28.

266. Find the dimensions of the magnet frame of a 4-pole machine for which the following data are given: Armature, 40 inches in diameter, 25 inches long, having 84 slots, $\frac{3}{16}$ inch wide and $1\frac{3}{4}$ inches deep; useful flux, 38,000,000 lines; factor of leakage, 1.3; magnet frame to be entirely of cast iron, cores to have rectangular cross-section; width of magnet cores and yoke to be equal to length of armature core.

Note:—To find the length of rectangular cores, determine the diameter of the equivalent circular cross-section, and apply the rules given in Par. **56**, Instruction Book.

267. Give sketch, drawn to scale, showing the complete magnetic circuit of the machine considered in the preceding example.

268. Name the advantages of circular magnet cores over rectangular and elliptical magnets.

269. In what type of machines is the employment of rectangular cores justified, and why?

270. State the only exceptional case in which a practical dynamo designer would employ curved magnet cores.

271. Give the formula for the total magnetizing force of a dynamo, and name the symbols employed.

272. State the fundamental law of the magnetic circuit.

273. Define permeance.

274. How is the permeance of a magnetic path expressed?

275. Give the formula for the magnetomotive force, in gilberts, required to produce a certain density in an iron path of given length.

276. Express the ampere-turns required for an iron path, if metric units are employed.

277. What is the formula for the ampere-turns of an iron path, in English units?

278. State the formula for the ampere-turns of an air path, if its length and density are given in metric units.

279. Give the expression for the ampere-turns of an air path in English units.

280. Define specific magnetizing force.

281. Give formula for the ampere-turns required for any portion of a magnetic circuit, if its length and specific magnetizing force are given.

282. State an approximate rule, used in preliminary calculations, for finding the ampere-turns required for compensating armature reaction.

283. Inspect closely the magnetizing curves of annealed wrought iron and ordinary cast iron (Fig. 27, Instruction Book), noting three or four characteristic points on each curve, and then plot these curves by locating the points so noted in a roughly drawn co-ordinate system and connecting the same by free hand.

284. What is the specific magnetizing force for soft cast steel at a density of 55,000 lines per square inch?

285. Give the specific magnetizing force of annealed wrought iron, if its density is 106,000 lines per square inch.

286. From Table 26, Instruction Book, determine the ampere-turns required for 25 inches of soft cast steel, if the density is 92,500 lines per square inch.

287. State the influence of the armature current upon the magnetic field.

288. Give formula for the demagnetizing number of ampere-turns of a smooth armature.

289. How can the angle of field distortion be approximately determined in case of a smooth armature?

290. How must the formula referred to in Question **288** be modified in case of a toothed armature?

291. What correction is necessary to apply the formula of Question **288** to a perforated armature?

292. State the average formula for the total number of compensating ampere-turns in case of wrought iron or cast steel polepieces.

293. Give the average formula for the total number of compensating ampere-turns in case of cast iron polepieces.

294. Determine the magnetizing force required for the bipolar smooth armature machine shown in answer to Question **259**, provided that the internal diameter of the armature discs is 3 inches.

295. The magnet frame of a bipolar dynamo is composed of wrought iron cores and yoke, and cast iron polepieces; the diameter of the cores is 14⅝ inches; the cross-section of the yoke is equal to that of the cores; the section of the polepieces is 408 square inches, that of the armature core is 170 square inches, and the gap area is 440 square inches; the length of the magnetic circuit in the cores and yoke is 80 inches, in the polepieces 28½ inches, in the armature 12½ inches, and in the air gaps 1½ inches; the armature flux is 11,000,000 lines; the factor of leakage is 1.3; the armature is wound with 50 turns; current output, 480 amperes; polar embrace, 75 per cent. Compute the exciting power required.

296. Find the number of ampere-turns required to excite the machine shown in answer to Question **260**, assuming the density in the teeth to be 100,000 lines per square inch, and the density in the solid portion of the armature core, 85,000 lines per square inch.

297. Assuming the machine given in Question **266** to be wound with 336 armature turns and having a current output of 600 amperes, what will be the exciting power required? Determine the flux densities in the air gaps and in the tooth-section for the dimensions shown in answer to Question **267**; to find the former, add 50 per cent. to the gap density at the pole faces to allow for concentration of the lines due to the teeth; and to obtain the latter, divide the armature flux by the tooth-section at the root of the teeth.

298. A 16-pole ring-type generator for 540 volts and 3,700 amperes has the following dimensions: External diameter of armature core, 144 inches; internal diameter, 124 inches; length, 31 inches; actual length occupied by the discs, 26½ inches; number of slots, 336; width of slots, 11/16 inch; depth of slots, 3⅛ inches; winding, 6 turns of armature conductor per slot; magnet frame, cast steel; cores, rectangular, 25 × 13 inches in cross-section, 16 inches long; yoke, 191 inches in diameter, 32 inches wide, 5 inches thick; pole plates, 32 inches long, 20 inches wide, 1¼ inches thick in center, embracing angles of 16° each; bore of polepieces, 144⅞ inches. The armature flux required to produce the rated output is 190,000,000 lines; leakage factor, 1.15. Calculate the ampere-turns necessary for the excitation of this machine, if the average flux density in the air gap is 50 per cent. in excess of the density at the pole faces, and if the mean length of the path in the air gap is 50 per cent. greater than the distance between pole face and armature.

299. Determine the magnetizing force required for a 10 pole dynamo from the following data: *Type:* radial inner-pole or star type, having cores supported radially from a central yoke in the form of a star. *Material:* cores and polepieces, wrought iron; yoke, cast iron. *Armature:* external core diameter, 120 inches; internal core diameter, 109½ inches; length, 20 inches; winding, 1,700 turns of rectangular copper bar. *Magnet frame:* diameter of polepiece circle, 107 inches; thickness at center of pole shoes, 3½ inches; polar embrace, 80 per cent.; magnet cores, rectangular cross-section, 12 inches thick, 19¾ inches wide, 16½ inches long; yoke, hollow decagonal prism, internal diameter 45 inches, length 23 inches, radial depth 11 inches. Current output, 1,400 amperes; armature flux, 90,000,000 webers; leakage factor, 1.2. Allow 25 per cent. in length of air gap for distortion of lines.

300. Find the ampere-turns required for a 6-pole ring-type 2,500-ampere generator, the following data being given: External diameter of armature, 96 inches; internal diameter, 60 inches; length, 34 inches; length actually occupied by iron discs, 28½ inches; number of slots, 264; size of slots, 2¾ × $\frac{9}{16}$ inch; winding, 2 conductors per slot, connected in drum fashion (by means of formed face connectors at end surfaces of armature core); magnet cores, wrought iron, 30¾ inches in diameter, 20 inches long, provided with wrought iron pole shoes, 34 × 34 × 2⅛ inches; yoke, cast steel, 161 inches in diameter, 38 inches wide, 10 inches deep; bore of pole-pieces, 96¾ inches; armature flux, 170,000,000 lines; factor of leakage, 1.18. Assume average gap density to be 1½ times the density at pole faces, and take length of air space 1½ times the actual gap distance.

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THE DESIGN OF DIRECT-CURRENT DYNAMOS AND MOTORS

301. Name the four methods of winding magnets for direct-current dynamos and motors.

302. How are constant-current arc-light generators excited?

303. How are the magnet coils of railway motors arranged?

304. How may direct-connected or geared motors be wound if they are intended for fairly constant load?

305. What winding is used for variable-speed motors?

306. What method of excitation is employed for constant-spee motors with variable load?

307. How are constant-voltage generators wound?

308. How must motors be wound if a strong starting torque is required?

309. What winding is used for constant-potential generators driven by power of widely varying speed?

310. What winding should be employed for motors required to run with constant speed at varying load?

311. One of two similar magnet cores is wound with 250 turns of wire and excited by a current of 15 amperes; the other is wound with 5,000 turns and excited by a current of ¾ of an ampere; which is the stronger magnet?

312. How does differential winding differ from ordinary compound winding?

313. Give formula for the number of turns of a series winding.

314. State rule for proportioning the size of wire for a series winding.

315. What sizes of wire are usually employed for the magnet winding of series arc-lighting machines?

316. Give the values of the specific cooling surface to be allowed for temperature rises of 20°, 30°, and 40° C., respectively.

317. Upon what facts is the calculation of the size of wire for a shunt winding based?

318. Give the formula for the approximate warm resistance of a copper wire of given length and diameter.

319. Why does the number of ampere-turns of a shunt magnet remain the same, irrespective of the number of turns, as long as the same size of wire is employed?

320. What formula is used for calculating the cross-section of a shunt wire? Explain the symbols employed.

321. How is the resistance of the field regulator of a shunt machine taken into account in determining the size of the magnet wire?

322. How does the shunt-voltage, entering the formula referred to in Question **320**, compare with the output voltage of a multipolar machine in which all field coils are connected in series?

323. How is the voltage between terminals of shunt winding determined from the output voltage, in case the field coils are connected in groups?

324. Give the value of the shunt voltage for a 500-volt, 8-pole ring type generator if its magnet winding is arranged in 2 groups of 4 coils each, allowing 12 per cent. of the voltage for overcoming regulator resistance.

325. What would be the shunt voltage, if all the coils of the machine referred to in the preceding question were connected in parallel?

326. The size of the shunt wire for a machine having been determined by means of formula (**49**), Instruction Book, what will be the consequence of employing too small a number of turns of this wire?

327. Give formula for the permissible power loss corresponding to a given temperature increase of a magnet.

328. What is the formula for the shunt current which causes a prescribed rise of temperature in a magnet of given size?

329. Express the maximum shunt current in case the temperature increase is limited to 50° C.

330. From Table **27**, Instruction Book, find the approximate winding height of a cylindrical magnet, 9″ in diameter, when used for a multipolar machine.

331. What is the approximate depth of winding on a 2½″ by 4¾″ rectangular core for a bipolar machine?

332. Compute the approximate length of the mean turn on a bipolar magnet 20 inches in diameter.

333. Find the approximate average length of turn on a 6½″ by 17″ multipolar magnet.

334. Determine the cooling surface of a bipolar magnet, 12″ in diameter and 18″ long, taking the external surface and both end surfaces of the coil.

335. Figure the cooling surface of a multipolar rectangular magnet, 4½″ by 12″ in cross-section, 6″ long, including but one of its end surfaces into the cooling surface.

336. Required the cooling surface of an oval magnet whose cross-section consists of a 4-inch square enclosed between two semi-circles, and whose length is 8 inches; the magnet is intended for a bipolar machine and only one of the end surfaces is to be taken into account for cooling.

337. The total number of ampere-turns required for normal load being given, how is the number of series ampere-turns of a compound dynamo found?

338. Give approximate formula for the total E. M. F. of an ordinary compound dynamo.

339. What is the formula for the approximate total E. M. F. of a 5 per cent. over-compounded dynamo?

340. How is the cross-section of the series field wire of a compound dynamo determined?

341. In which case must the size of the series wire, obtained by the rule referred to in the preceding question, be increased?

342. By means of Table **28**, Instruction Book, determine the number of turns of No. 8 wire that can be put in each layer of a coil 12½" long.

343. How many turns of No. 14 wire can be wound in a coil space 8¾" long and 1½" high?

344. A magnet of 17" diameter is wound with 15,000 turns of No. 19 B. & S. wire to a height of 1⅞ inches; find the bare and covered weight of the wire and its resistance at 20° C.

345. Calculate a series winding for the machine given in Question **295** (Part 3), supposing that its armature is wound for 5,000 volts and 10 amperes, and assuming that the magnetizing force required for its excitation was obtained as 20,000 ampere-turns; the length of each magnet core is 22 inches; allow a wire cross-section of 1,650 circular mils per ampere.

346. The machine considered in Question **295** is to be shunt-wound for an output of 125 volts and 480 amperes; the winding to be calculated for a magnetizing force of 20,000 ampere-turns and a temperature increase of 20° C.; depth of magnet winding 1½ inches; allow a drop of 15 per cent. for regulating resistance, and take as cooling surface the cylindrical portion of the magnets only.

347. Compute the winding in case it is desired to over-compound the machine given in the preceding example for a line loss of 6 per cent.; both the series and the shunt coils to be connected in series; limit of temperature rise, 25° C.; data for magnetic circuit given in Question **295**; speed, 700 revolutions per minute; the armature is drum-wound and has a resistance of .01 ohm.

348. Calculate a shunt winding for the 2,000 K. W. railway generator given in Question **298**; temperature rise, 30° C.; percentage of E. M. F. absorbed by regulating resistance, 10 per cent.; all magnet coils connected in series; exciting power required, 33,000 ampere turns.

349. The machine of the preceding example is to be over compounded for a loss of 5 per cent ; temperature increase, 35° C.; all the series coils to be connected in parallel, all shunt coils in series; dimensions of machine and magnetic data same as in Question **298**; speed, 70 revolutions per minute; number of armature conductors, 2,016; armature resistance, .002 ohm.

350. A four-pole 25-K.W. direct-driven 150-volt generator is designed as follows: *Armature*, smooth ring, 27″ external diameter, 19¼″ internal diameter, 12¾″ long; winding, 144 coils of 5 turns each; resistance, .036 ohm; length of magnetic path in armature core, 15″. *Yoke*, cast iron, octagonal shape, 54″ across flats; width, 11½″; radial thickness, 6″; length per magnetic circuit, 33″. *Magnets*, cast steel ; diameter, 9″; length, 5¾″. *Pole-pieces*, cast steel ; bore, 28¼″; pole angle, 63°. Speed, 300 revolutions per minute; factor of magnetic leakage, 1.3. Compute a shunt winding for a 40° C. rise, allowing 15 per cent. of output E. M. F. for shunt regulator, and taking as cooling area of the coils their cylindrical surface and one end surface. The four shunt coils to be connected in series.

351. Required a 5 per cent. over compound winding for the machine given in the preceding question. Temperature rise, 45° C.; all coils of both series and shunt winding to be connected in series.

352. Assuming that the magnetizing force required for the generator given in Question **300** was found to be 42,000 ampere-turns, determine a shunt winding for a temperature increase of 30° C, allowing 10 per cent. of the terminal E. M. F., which is 600 volts, for regulating resistance; coils connected in series.

353. From the data given for a 1,500 K. W. railway generator in Question **300**, compute a compound winding for a rise of 25° C., provided that the speed is 250 revolutions per minute and the armature resistance .0024 ohm. The series coils to be connected in two groups and the shunt coils in three groups.

354. Define electrical efficiency.

355. Define commercial efficiency.

356. Define gross efficiency.

357. Give the general formula for the electrical efficiency of a generator.

358. State the general formula for the electrical efficiency of a motor.

359. By what formula is the electrical efficiency of a series-wound generator calculated?

360. Give formula for the electrical efficiency of a shunt-wound generator.

361. Give formula for the electrical efficiency of a compound-wound generator.

362. How do the efficiency formulas for a motor differ from the corresponding formulas for a generator?

363. Express the armature current of a shunt or compound-wound generator, and that of a shunt or compound-wound motor, in terms of the terminal and shunt currents.

364. State the usual limits of the electrical efficiency of modern machines.

365. Define the intake and output of dynamo-electric machines.

366. Give the general formula for the commercial efficiency of a generator.

367. Give the general formula for the commercial efficiency of a motor.

368. Give the formula for the commercial efficiency of a compound wound generator.

369. Give the formula for the commercial efficiency of a shunt-wound motor.

370. By means of Table **29**, Instruction Book, find the approximate power-loss by friction in a 35 K.W. dynamo.

371. Between what limits does the commercial efficiency of modern machines usually range?

372. Upon what does the commercial efficiency of a dynamo depend?

373. Give formula for the commercial efficiency of a belt-driven generator, if the data for computing the mechanical power transmitted by its belt are known.

374. State the average percentage of power loss in a horizontal dynamo belt.

375. How is the gross efficiency of a dynamo-electric machine obtained?

376. Give the practical limits of the gross efficiency of modern dynamos.

377. Define the weight-efficiency of a dynamo.

378. What does a high weight-efficiency indicate?

379. Give the usual limits of the weight-efficiency for low, medium, and high speed dynamos, respectively.

380. State the weights per cubic inch of wrought iron, cast iron, copper, and brass.

381. Give the average percentage by which the weight of the principal parts (magnet frame, armature windings, bearings and bed, or brackets) of a high-voltage machine must be increased to allow for accessory parts.

382. By what average percentage must the weight of the principal parts of a low-voltage machine be increased to obtain its total weight?

383. Name an approximate method for computing the weight of a toothed armature.

384. Describe the accurate method of calculating the weight of a toothed armature core.

385. Compute the electrical efficiency of a series-wound 25 arc-light generator (1,250 volts, 10 amperes), whose armature resistance (warm) is 5 ohms, and whose field resistance is 6 ohms.

386. A shunt-wound 150-K.W. 250-volt generator has an armature resistance of .01 ohm, a field resistance of 42 ohms, and a regulator resistance, at normal output, of 8 ohms; determine its electrical efficiency.

387. Find the electrical efficiency of a compound-wound, 125-volt, 500-watt generator, if its armature resistance is 3 ohms, its series field resistance 1.5 ohms, and its shunt resistance 312 ohms.

388. What is the electrical efficiency of a ½ H.P. series motor, taking 4 amperes at 125 volts, if its armature has a resistance of 4.3 ohms and its field a resistance of 1.2 ohms?

389. Calculate the electrical efficiency of a shunt-wound 500-volt motor which takes 12 amperes and has an armature resistance of 2.65 ohms, and a magnet resistance of 943 ohms.

390. The armature resistance of a compound-wound motor is .085 ohm, its series field resistance .025 ohm, and its shunt resistance 88 ohms; the motor consumes a current of 80 amperes on a 220-volt circuit; find its electrical efficiency.

391. Find the commercial efficiency of the arc-light generator of Question **385**, if it has a hysteresis loss of 275 watts, and an eddy current loss of 50 watts.

392. Required the commercial efficiency of the 150 K.W. shunt dynamo given in Question **386**; its hysteresis loss is 1,100 watts and its eddy current loss is 130 watts.

393. The power absorbed by hysteresis and eddy currents in the 500-watt compound-wound generator referred to in Question **387** is 13 watts; what is its commercial efficiency?

394. The $\frac{1}{2}$ H.P. series motor of Question **388** has a total iron loss of 12 watts; determine its commercial efficiency.

395. Compute the commercial efficiency of the shunt motor referred to in Question **389**, if its iron losses are known to be 60 watts.

396. What is the commercial efficiency of the compound-wound motor described in Question **390**, if its hysteresis loss is 200 watts and its eddy current loss is 50 watts?

397. Find the commercial efficiency of a 75 H.P. motor from the following test: E. M. F. of supply circuit, 440 volts; current taken by motor, 140 amperes; speed of motor, 750 revolutions per minute; pulley diameter, 21 inches; belt tension, tight side, 950 pounds; slack side, 350 pounds.

398. Compute the commercial efficiency of the generator given in Questions **386** and **392**, including the loss in belting, if it is driven by a vertical belt. Use the average of the respective percentages given in Table **30**, Instruction Book.

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